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LIFE CYCLE ASSESSMENT (LCA) OF NEWSPRINT PRODUCTION AT AN INTEGRATED MILL

ERICA SOLEDAD SALAZAR ZÁRATE
DÉPARTMENT DE GÉNIE CHIMIQUE
ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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Ce mémoire intitulée:

LIFE CYCLE ASSESSMENT (LCA) OF NEWSPRINT PRODUCTION AT AN INTEGRATED MILL

présenté par: SALAZAR-ZÁRATE Erica-Soledad

en vue de l'obtention du diplôme de: Maîtrise ès sciences appliquées

a été dûment accepté par le jury d'examen constitué de:

M. COMEAU Yves, Ph.D., président

M. STUART Paul, Ph.D., membre et directeur de recherche

M. SAMSON Réjean, Ph.D., membre et codirecteur de recherche

M. CHAN Albert W., Ph.D., membre

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RÉSUMÉ

L'objectif de ce projet de recherche est de proposer une procédure systématique considérant l'incertitude sur les paramètres pour interpréter les résultats d'une analyse du cycle de vie (ACV) dont le but principal est l'identification d'opportunités d'amélioration de la performance environnementale. La procédure est illustrée par une étude de cas traitant de la production de papier journal standard et couvrant les étapes d'extraction des matières premières à la distribution du papier journal.

La méthodologie ACV est standardisée par l'Organisation internationale de standardisation (ISO) à l'aide d'une série de normes qui constituent la famille ISO 14040. ISO 14043 est l'une des normes de cette famille et a pour sujet la phase d'interprétation de l'ACV. Cette dernière propose une procédure générale consistant en l'identification des points significations et en une série de vérifications. De plus, il y est recommandé de compléter ces vérifications par l'évaluation de l'incertitude et de la qualité des données. Cependant, puisque les recommandations d'ISO à ce propos consistent seulement en des lignes directrices générales, ces évaluations ont typiquement été exclues des études ACV.

L'industrie papetière est un secteur industriel important dans le contexte canadien ayant plusieurs motivations pour continuellement améliorer sa performance environnementale et ce, d'une perspective cycle de vie. Dans ce contexte, l'application de l'ACV pour l'analyse de procédés a augmenté au cours des dernières années et on constate un potentiel pour l'utilisation de cet outil pour évaluer différentes options de procédé. De cette façon, on peut constater l'effet de modifications au procédé sur toute la chaîne de produit. Il devient alors de plus en plus important de développer des procédures d'interprétation des résultats systématiques permettant la prise en considération des

incertitudes afin que les conclusions et les recommandations soient plus crédibles et facilement applicables.

Pour le système étudié, un modèle ACV de référence incluant tous les éléments requis par les normes ISO a été développé. Une attention particulière a été portée à la modélisation du système et aux choix méthodologiques qui ont été inspirés par le contexte de l'étude, la connaissance du procédé et des études antérieures reliées. Des interactions avec le personnel de l'usine à l'étude ainsi qu'avec des experts en pâtes et papiers et en ACV ont permis le raffinement du modèle afin qu'il représente le plus fidèlement possible le système réel.

L'approche proposée pour l'interprétation des résultats a été basée sur l'objectif de l'étude et inspirée par les travaux précédents. Celle-ci a les avantages suivants : elle est focalisée sur les paramètres plutôt que sur les processus élémentaires, elle considère l'incertitude des paramètres, elle évite l'utilisation d'éléments de pondération et elle utilise une technique d'analyse de sensibilité simple qui ne nécessite pas de distribution probabiliste sur les données. Cette procédure est orientée vers l'identification d'opportunités permettant l'amélioration environnementale d'une perspective cycle de vie par l'évaluation comparative des résultats d'analyses de sensibilité sur les paramètres directement contrôlés par l'usine tels que la consommation d'électricité ou les émissions à l'effluent. L'analyse est complétée par une évaluation de la sensibilité des paramètres d'arrière-plan ainsi que des paramètres non directement contrôlés par l'usine et ayant été modélisés à partir de sources de données secondaires tels que les émissions dues à la production de produits chimiques utilisés par l'usine. Cette dernière étape permet de concentrer les efforts d'amélioration de la qualité des données du modèle sur les paramètres ayant une influence significative sur les résultats. De plus, l'influence de deux choix méthodologiques clés sur les résultats de caractérisation a été évaluée en modifiant le modèle de façon à inclure des approches alternatives trouvées dans la littérature et en comparant les résultats obtenus avec les résultats originaux.

Lorsque les paramètres de procédé les plus significatifs ont été identifiés, certains scénarios permettant la réduction des impacts environnementaux potentiels associés à ces paramètres ont été développés. Le développement de ces scénarios a aussi été inspiré des stratégies environnementales courantes spécifiques à l'industrie papetière. Encore une fois, le modèle de référence a été modifié de façon à réfléchir les scénarios et les résultats ont été comparés avec les résultats originaux afin d'illustrer les bénéfices des alternatives proposées.

La sensibilité des résultats de catégories d'indicateur à neuf paramètres de procédés a été évaluée. Les résultats ont montré que la plupart des catégories d'impact étaient sensibles à la consommation d'électricité et de gaz naturel. L'eutrophisation, quant à elle, était principalement sensible à l'émission par l'usine d'azote dans l'effluent liquide. Par conséquence, il y a une opportunité pour l'usine étudiée d'améliorer sa performance environnementale d'une perspective cycle de vie en réduisant les impacts reliés à ces paramètres.

La comparaison des résultats de sensibilité pour 18 paramètres d'arrière-plan a démontré de plus grandes valeurs de sensibilité pour les émissions de substances appauvrissant la couche d'ozone par la production de DPTA (i.e. halon, et CFC-114), les émissions atmosphériques de Hg et As par la production d'électricité, l'émission atmosphérique de méthane par les sites d'enfouissement et les émissions liquides de As par la production de NAOH. Pour cette raison, les efforts d'amélioration de la qualité des données devraient être concentrés sur ces paramètres. Finalement, l'évaluation de l'incertitude due aux choix méthodologiques clés, c'est-à-dire l'approche d'imputation utilisée pour les opérations de la scierie et l'exclusion de la Cueillette des papiers usés, n'ont montré aucun effet significatif sur les résultats de caractérisation.

L'analyse des scénarios reliés à l'énergie a permis l'évaluation de l'effet de l'augmentation de la production de pâte recyclée, l'implantation d'un système de cogénération sur site et une combinaison de ces deux dernières stratégies. Les résultats ont montré des bénéfices significatifs pour les catégories d'impact étant les plus sensibles à la consommation électrique (par exemple, le réchauffement planétaire). Ces résultats étaient plus significatifs pour la combinaison des deux stratégies. Il a été montré que les bénéfices obtenus dépendaient fortement du mélange d'énergie utilisé pour la production d'électricité. Un autre groupe de scénarios a été utilisé pour évaluer l'effet de technologies alternatives de traitement de l'effluent de l'usine. Les technologies évaluées sont le traitement tertiaire et une technologie permettant d'atteindre l'objectif de zéro effluent. L'analyse de ces technologies a ciblé l'eutrophisation dû à sa forte sensibilité aux émissions de nutriments dans l'effluent de l'usine. Les résultats ont montré des réductions allant de 50 à 80%, le plus de bénéfices étant obtenus par la technologie d'effluent zéro qui élimine toute contribution de l'effluent de l'usine à l'eutrophisation.

La méthodologie proposée ainsi que les résultats obtenus démontrent comment un modèle ACV de référence peut être systématiquement utilisé afin d'identifier des opportunités de procédé permettant d'amélioration de la performance environnementale d'une perspective cycle de vie. L'inclusion de l'incertitude sur les paramètres d'arrière-plan dans l'évaluation permet l'identification de l'effet de l'incertitude dans les données sur les résultats de caractérisation. De plus, l'analyse de la contribution des paramètres de procédé de l'usine permet l'identification et la recommandation d'opportunités non seulement d'amélioration de la performance environnementale, mais aussi de la qualité des données du modèle.

Par l'analyse de scénarios, il a été démontré que les opportunités d'amélioration identifiées de façon consistante avec les stratégies environnementales courantes dans l'industrie papetière impliquaient potentiellement une réduction dans les résultats de caractérisation. L'utilisation d'un modèle de référence pour l'évaluation d'options de procédé a aussi été illustrée.

Finalement, il a été démontré que les résultats et les conclusions tirées pour l'étude de cas n'étaient valides que pour le système étudié et ne pouvaient être généralisées dû à l'influence dramatique de la source d'électricité primaire qui dépend de l'emplacement de l'usine.

ABSTRACT

This research project is intended to propose a systematic procedure to interpret the results of Life Cycle Assessment (LCA) studies oriented towards the identification of improvement opportunities for environmental performance, taking into account parameter uncertainties. The proposed approach is illustrated with a case study from the pulp and paper industry, namely the production of standard newsprint from raw material extraction to newsprint distribution.

LCA methodology is standardized by the International Standardization Organisation (ISO) through a series of guidelines that constitute the ISO 14040 family. ISO 14043, whose topic is the interpretation phase, proposes a general procedure consistent with the identification of significant points and the performance of interpretation checks. Furthermore, ISO recommends complementing these checks with uncertainty and data quality assessments. Nonetheless, only general frameworks about how to handle this ISO recommendation are available at this time and, consequently, this has typically been excluded from LCA case studies.

The pulp and paper industry is an important industrial sector in the Canadian context with many motivations for continuously improving its environmental performance from a life cycle perspective. In this context, the application of LCA in process analysis has increased in recent years and there is a potential of using LCA in the assessment of process variants, meaning to analyze the effect of mill modifications in the performance of the whole product chain. Therefore, the systematic interpretation of the results considering the study uncertainties becomes necessary in order to draw more credible and applicable conclusions and recommendations.

For the system studied in this project, a LCA baseline model was developed including all the elements required by the ISO guidelines. Special attention was focused on system modeling and methodological choices which were based on the context of the study, process know how and previous related studies. Interaction with mill personnel as well as with experts in the pulp and paper industry and LCA allowed for the refining of the model in order to better reflect the real system.

The proposed approach for the results interpretation was based on the goal of the study and inspired by previous works. It has the following advantages: it is focused on parameters instead of on unit processes, it takes into account parameter uncertainties, it avoids the use of valuation elements and it uses a simple sensitivity technique that does not require data on probability distribution. This procedure is oriented towards the identification of mill opportunities to improve the life cycle performance by comparatively evaluating the LCA results sensitivity on process parameters over which the mill has direct control, such as electricity consumption or effluent emissions. This analysis is complemented with the evaluation of results sensitivity on background parameters or those over which the mill does not have direct control and that were modeled based on secondary sources, such as emissions from the production of chemicals used in the mill. This latter step allows for focusing the efforts on improving the model data quality only on parameters that have significant influence on the final results. Additionally, the influence of two key methodological choices on the impact category results was evaluated, by modifying the baseline model to include alternative approaches identified in the literature and comparing the results against those from the baseline model.

After identifying the most significant mill process parameters, some scenarios oriented towards the reduction of their potential environmental impacts were developed based on current environmental strategies for the pulp and paper industry. Again, the baseline model was modified to reflect the designed scenarios and the results were compared

with those from the baseline model in order to show the potential benefits of the proposed alternatives.
The sensitivity of the category indicator results on nine process parameters was comparatively evaluated. The results showed that electricity and natural gas consumption have high sensitivity in most of the impact categories and that eutrophication is mainly sensitive to mill nitrogen emissions to water. Therefore, the studied newsprint mill has the opportunity to improve the life cycle's environmental performance by reducing the impacts related to these process parameters.

The comparison of sensitivity results for 18 background parameters resulted in higher sensitivity values for ozone depleting air emissions from EDTA production (i.e., halon and CFC-114), air emissions of Hg and As from electricity production, methane air emissions from landfill and water emissions of As from NaOH production. Therefore, efforts to improve the inventory data quality should be primarily focused on these parameters. Finally, the assessment of uncertainties due to key methodological choices, namely the by-product allocation approach for sawmill operations and the exclusion of wastepaper collection, showed no significant effects on the characterization results.

The analysis of scenarios focused on energy issues assessed the effects of increasing recycled pulp production, the implementation of an on-site cogeneration system and a combination of these two. The results showed significant benefits for the impact categories with higher sensitivity to electricity consumption (i.e., global warming), with more benefits from the combined scenario. It was found that these benefits strongly depend on the at-source power mix used for the electricity production. Another group of scenarios assessed the effects of alternative treatment technologies for the newsprint mill effluents, namely tertiary treatment and zero effluent technology. The analysis of the proposed technologies was focused on the eutrophication impact category due to its strong sensitivity to nutrient emissions in the mill effluent. The results showed reductions from 50 to 80%, with more benefits from the zero effluent scenario, which eliminates the mill effluent contribution to eutrophication.

The proposed methodology and the obtained results demonstrate how a LCA baseline model can be systematically evaluated in order to identify mill opportunities to improve environmental performance of the production chain. The inclusion of parameter uncertainty in the assessment allows for the identification of how impact category results are affected by the uncertainty in the data of background parameters and by the contribution of mill process parameters. Recommendations on the opportunities to improve not only the environmental performance but also the model data quality can therefore be made.

By the scenario analysis, it was demonstrated that the identified improvement opportunities, along with the current environmental strategies in the pulp and paper industry, actually involve potential reductions on the category indicator results. It was also illustrated that the baseline model can be used for future applications in the assessment of process variants.

Finally, it was demonstrated that the results and conclusions drawn for the case study are only valid for the system studied and they can not be generalized for other systems due to the dramatic influence of the primary electricity source, which depends on the mill location.

CONDENSÉ EN FRANÇAIS

INTRODUCTION

L'application de l'analyse du cycle de vie (ACV) pour l'analyse de procédé s'est largement répandue au cours des dernières années. Cependant, les études de cas effectuées présentent certaines imperfections méthodologiques surtout en ce qui concerne les éléments optionnels selon ISO tels que la pondération et l'analyse d'incertitude lors de la phase d'interprétation. Ce projet de recherche est axé sur ce dernier élément.

Lorsque l'application prévue d'une ACV est d'analyser un procédé, l'objectif consiste généralement en l'identification d'opportunités pour améliorer la performance environnementale du système étudié. Cette identification ce fait généralement par le biais de l'analyse de la contribution de chacun des processus élémentaires à chacune des catégories d'impact. Cette approche peut cependant s'avérer problématique lorsque diverses catégories d'impact sont évaluées et que les contributions des processus élémentaires varient selon la catégorie d'impact. À ce jour, les utilisateurs d'ACV contournent ce problème en pondérant les catégories d'impacts ou en identifiant les opportunités pour chacune des catégories d'impact. La principale faiblesse de ces deux approches est qu'une analyse complémentaire d'incertitude n'est généralement pas présente.

Dans ce projet de recherche, nous proposons une approche alternative d'interprétation qui cible les paramètres du modèle et considère l'incertitude reliée à ceux-ci. Les paramètres de procédés qui devraient être ciblés pour l'implantation d'améliorations ainsi que les paramètres d'arrière-plan pour lesquels il est nécessaire d'améliorer la qualité des données, pourront ainsi être identifiés de façon simultanée. L'approche proposée se base sur la comparaison de la sensibilité des résultats d'indicateurs à différents paramètres du modèle, évitant ainsi la subjectivité reliée à l'étape de pondération et utilisant une technique de sensibilité fiable et facile d'utilisation pour laquelle aucune connaissance de la distribution probabiliste des données n'est nécessaire.

De façon à illustrer cette nouvelle approche, un modèle ACV de référence a été développé. Le système étudié est la production de papier journal standard contenant 20% de pâte recyclée. Les frontières du système s'étendent de l'extraction des matières premières jusqu'à la distribution du papier journal (i.e., du berceau à la porte). La chaîne de production principale inclue les activités forestières, la scierie et l'usine de papier journal. Ces trois unités d'affaires appartiennent à la même compagnie située dans le nord de l'Ontario. Toutes les activités contrôlées directement par la compagnie et reliées au procédé de production de papier journal sont incluses (par exemple, services de l'usine, traitement des déchets, transports, etc.). Les procédés d'arrière-plan inclus dans le modèle sont reliés à la production de l'électricité, des combustibles et des produits chimiques utilisés dans le procédé de production du papier journal.

Les objectifs généraux de ce projet de recherche sont :

- Développer un modèle ACV de référence pour la production de papier journal approprié pour l'évaluation d'options de procédé;
- Proposer une procédure systématique pour l'interprétation des résultats du modèle de référence orientée vers l'indentification opportunités reliées à l'usine de papier journal afin d'améliorer sa performance environnementale dans une perspective cycle de vie;
- Montrer les bénéfices des opportunités d'amélioration identifiées par l'évaluation de diverses configurations de procédé reflétant les stratégies environnementales spécifiques à l'industrie papetière.

L'hypothèse de recherche proposée est la suivante:

Les résultats d'un modèle ACV de référence peuvent être utilisés de façon systématique et pratique afin d'identifier des opportunités de procédé permettant d'améliorer la performance environnementale du cycle de vie par la réalisation d'analyses de sensibilité, séparant donc de ce fait les éléments de pondération de l'évaluation.

MÉTHODOLOGIE

Les activités de recherche effectuées pour cette étude sont présentées à la Figure 1. Elles sont regroupées selon les quatre phases de la méthodologie ACV et incluent :

Définition de l'objectif et du champ de l'étude:

Elle implique la définition et la justification des choix méthodologiques principaux tels que:

- *Objectif de l'étude*: l'identification d'opportunités de procédé permettant d'améliorer la performance environnementale dans une perspective cycle de vie;
- *Unité fonctionnelle*: 1 admt de papier journal;
- *Frontières du système*: de l'extraction des matières premières à la distribution du papier journal.

Analyse de l'inventaire

Au cours de cette phase, une activité importante a consisté en la compréhension du système de façon à pouvoir le modéliser. Dans cette optique, des diagrammes d'écoulement pour chacun des procédés de l'usine ont été développés. Par la suite, le système a été modélisé en utilisant des données spécifiques au site pour tous les procédés de l'usine ainsi que pour la production d'électricité. Des données provenant de bases de données commerciales on été utilisées pour la production des combustibles et des produits chimiques ainsi que pour l'enfouissement. L'inventaire couvrant toutes les étapes considérées dans l'étude a été agrégé pour 1 admt de papier journal en utilisant le logiciel Simapro 5.1. Ce premier modèle d'inventaire a été raffiné à la suite d'une visite de l'usine et d'une meilleure compréhension du procédé réel.

Évaluation des impacts

La principale tâche de cette phase a été la sélection des catégories d'impacts, des indicateurs de catégorie et des modèles de caractérisation. La sélection a été faite sur la base du contexte et des objectifs de l'étude et en accord avec la norme ISO 14042 et avec les meilleures pratiques disponibles selon le SETAC. Les facteurs de caractérisation des modèles (i.e. IPCC pour le réchauffement planétaire, WMO pour la destruction de la couche d'ozone et TRACI pour les impacts locaux et régionaux) on été inclus dans Simapro 5.1 qui a effectué la classification et la caractérisation des catégories d'impact. Finalement, les résultats de caractérisation on été obtenus pour 1 admt de papier journal.

Interprétation des résultats

Les activités effectuées au cours de cette phase constituent la principale contribution méthodologique du projet. Les résultats d'évaluation des impacts ont été analysés pour deux types d'incertitude : l'incertitude sur les paramètres et l'incertitude due aux choix méthodologiques.

La première étape de l'évaluation des paramètres consiste en l'identification des paramètres clés du modèle sur la base de leur contribution aux résultats de caractérisation et de l'incertitude sur les données. La contribution a été calculée en utilisant Simapro 5.1 et l'incertitude sur les données a été évaluée qualitativement à l'aide d'indicateurs de qualité des données (DQI). Par la suite, l'étendue de l'incertitude a été définie pour les paramètres clés sélectionnés et celle-ci a été utilisée afin de calculer la sensibilité des résultats de caractérisation à ces paramètres. L'identification des opportunités d'amélioration de la performance environnementale dans une perspective cycle de vie a été effectuée en comparant les résultats de sensibilité de chacun des paramètres de procédé de l'usine identifiés. Au même moment, les paramètres pour lesquels une meilleure qualité des données était souhaitable ont aussi été identifiés. Ceux-ci ont été définis par la comparaison des résultats de sensibilité pour les paramètres d'arrière-plan (i.e. les paramètres pour lesquels la compagnie n'a pas de contrôle direct). Les paramètres d'avant-plan ont ensuite été évalués plus en profondeur à l'aide d'analyses de scénarios. Des scénarios alternatifs ont été développés en utilisant les paramètres ayant une influence significative sur la performance du cycle de vie et s'inspirant des stratégies environnementales courantes spécifiques à l'industrie papetière. Le modèle a été modifié afin de réfléchir les scénarios développés et les résultats obtenus ont été comparés aux résultats originaux.

L'influence de deux choix méthodologiques clés, l'approche d'imputation due aux coproduits à la scierie et l'inclusion de la collection des papiers usés dans le système, a également été évaluée. Le modèle a aussi été modifié afin d'inclure des approches alternatives proposées dans la littérature et les résultats ont été comparés aux résultats originaux.

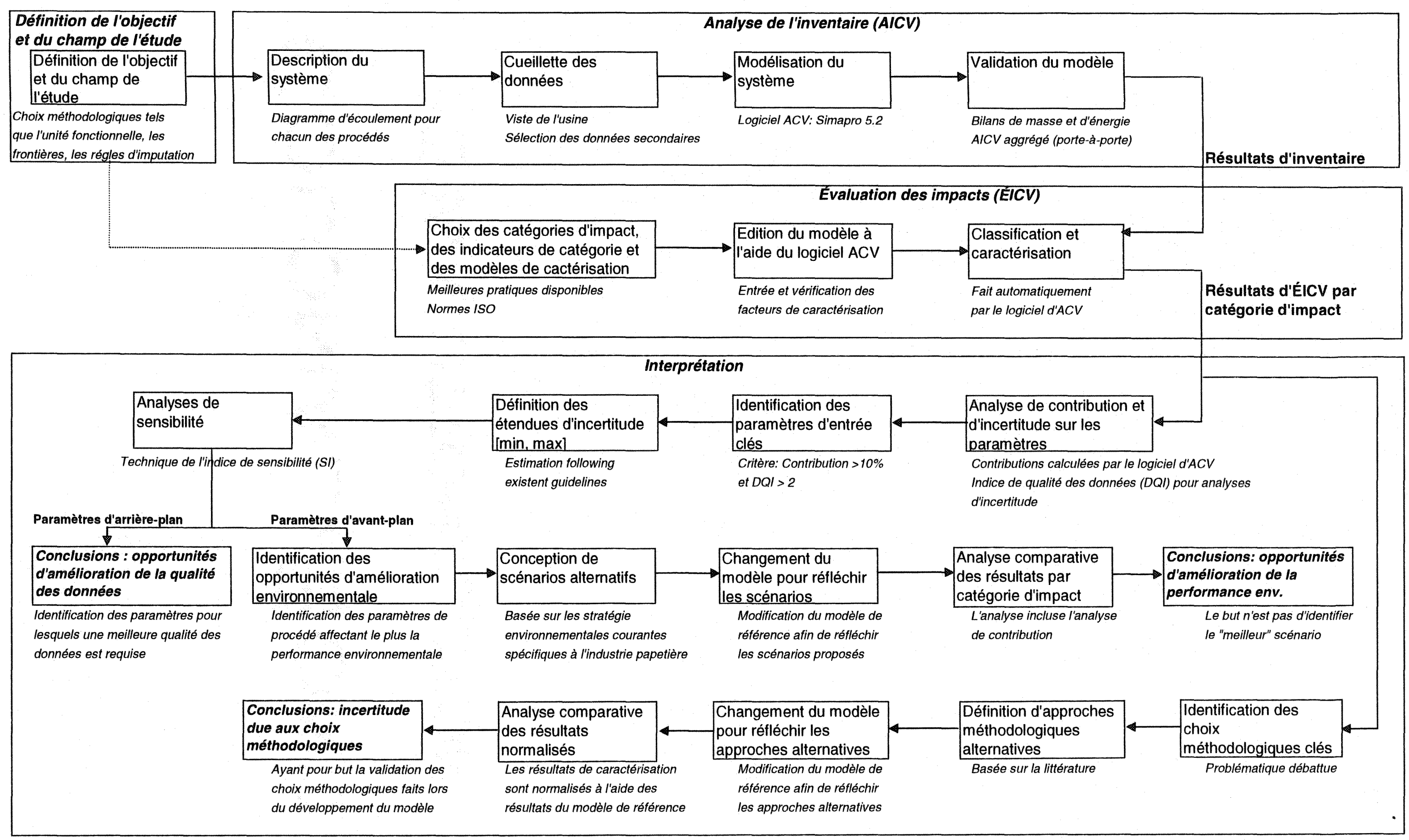

Figure 1: Méthodologie pour l'analyse du cycle de vie de la production de papier journal

RÉSULTATS

Les données relatives aux paramètres de procédés de l'usine ont une incertitude faible comparativement à celles relatives aux paramètres d'arrière-plan. Les résultats de sensibilité des paramètres de procédé dépendent surtout de leur contribution. La sensibilité de neuf paramètres de procédé a été calculée par le ratio du changement dans les résultats de caractérisation au changement du paramètre due à son étendue d'incertitude définie par la valeur minimale et la valeur maximale de la série de données utilisée lors de la modélisation de l'inventaire. Une comparaison des résultats de sensibilité entre ces paramètres a montré que la majorité des catégories d'impact était sensible à la consommation d'électricité et de gaz naturel et que l'eutrophisation était surtout sensible à l'émission d'azote dans l'effluent de l'usine (voir Figure 2). Par conséquence, ces derniers paramètres ont été sélectionnés pour l'application d'améliorations environnementales.

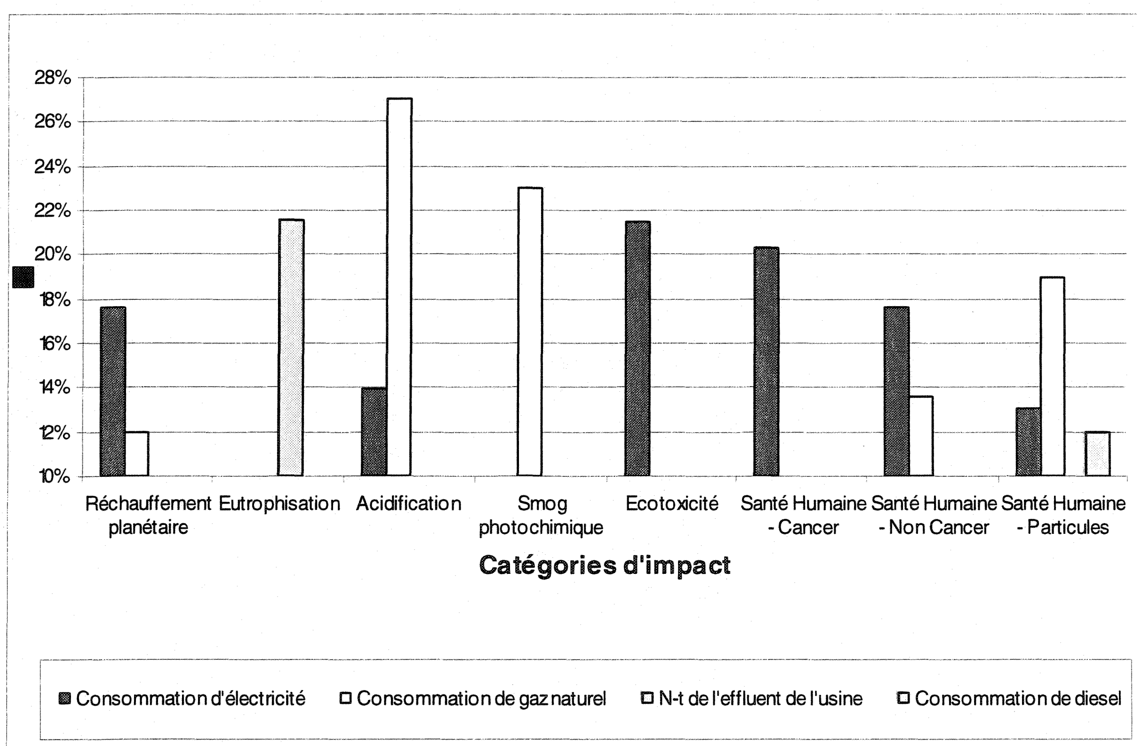

Figure 2: Résultats d'analyses de sensibilité sur les paramètres procédés de l'usine

D'autre part, les paramètres d'arrière-plan sont plus incertains puisque qu'ils sont tirés en grande partie de la littérature et de bases de données commerciales. Pour cette raison, ils ont montré des résultats de sensibilité supérieurs à ceux obtenus pour les paramètres procédés de l'usine. Une comparaison entre les paramètres d'arrière-plan a montré que les résultats de caractérisation étaient surtout sensibles à l'émission de substances appauvrissant la couche d'ozone par le procédé de production de DPTA (i.e. halon et CFC-114), aux émissions atmosphériques de Hg et de As par la production d'électricité, aux émission de méthane par les sites d'enfouissement et à l'émission de As dans l'eau par la production de NaOH. Dans tous les cas, il est recommandé d'amorcer l'amélioration de la qualité des données par la détermination des étendues d'incertitude, puis d'effectuer une évaluation complémentaire de sensibilité et, finalement, de déterminer s'il est nécessaire d'améliorer la qualité des données pour ces paramètres.

Par l'évaluation de l'incertitude due aux choix méthodologiques, il a été montré que l'approche d'imputation utilisée pour les opérations de la scierie n'affectait pas de façon significative les résultats de caractérisation. L'approche utilisée dans le modèle de référence consiste en l'imputation de la charge environnementale au bois d'œuvre, aux copeaux et au combustible provenant de déchets de bois sur une base massique. Il y a cependant un débat à savoir si l'on doit imputer une partie de la charge environnementale aux copeaux et au combustible puisque le bois d'œuvre est le produit principal de la scierie. L'évaluation a montré qu'en n'imputant aucune charge environnementale au combustible, les résultats de caractérisation demeuraient inchangés. En revanche, en imputant cette charge environnementale seulement au bois d'œuvre, une différence de 2 à 13% a été observée avec les résultats originaux. Bien entendu, les plus gros écarts ont été observés pour les catégories d'impacts ayant une plus grande contribution provenant du transport des rondins (santé humaine et formation de smog).

Le deuxième choix méthodologique ayant été analysé est l'exclusion du transport du papier usé des résidences aux installations de récupération dans les villes (i.e. la cueillette du papier usé). Les résultats ont démontré que l'exclusion de cette activité était négligeable pour toutes les catégories d'impact car sa contribution est très faible (<<1%), la plus élevée étant 0.00435% pour la catégorie d'impact santé humaine – particules.

Une analyse de scénario complémente l'identification des opportunités d'amélioration de la performance environnementale dans une perspective cycle de vie par l'implantation de modifications au procédé de production de papier journal. Les scénarios ont été développés de façon à réduire les impacts potentiels dus à la consommation d'électricité et de gaz naturel ainsi que ceux dus à l'émission d'azote dans l'eau. Ces scénarios ont donc été classifiés en deux catégories : les scénarios orientés énergie et les scénarios orientés effluent.

Les scénarios orientés énergie consistent en l'augmentation de la production de pâte recyclée, laquelle nécessite moins d'énergie que la production de pâte produite à partir de fibres vierges, la cogénération d'électricité sur site à partir de gaz naturel et de biomasse et la combinaison de ces deux dernières options. Les résultats ont montré que l'on n'obtenait pas un bénéfice pour toutes les catégories d'impact. En effet, une amélioration a été observée pour les catégories d'impact hautement sensibles à la consommation d'électricité (i.e. réchauffement planétaire), alors que les catégories d'impacts plus sensibles à la consommation de gaz naturel (i.e. formation de smog) ont été négativement affectées. Cette dernière observation est due au fait que, dans tous les cas, la consommation de gaz naturel augmente.

Puisque la production d'électricité contribue de façon significative à la majorité des catégories d'impact, l'influence du modèle de production de l'électricité a été analysée en utilisant la production typique d'électricité de trois différentes provinces canadiennes. Il a été montré que le modèle de production de l'électricité, lequel dépend de l'emplacement de l'usine, avait un effet dramatique sur les résultats.

Dans le cas des scénarios orientés effluent, l'analyse a ciblé les résultats d'eutrophisation parce que ceux-ci présentaient une sensibilité élevée aux émissions d'azote. Trois scénarios ont été analysés : l'implantation d'un traitement tertiaire par coagulation/floculation pour la même quantité d'effluent, la réduction de l'effluent combinée à un traitement tertiaire et l'élimination de l'effluent par l'implantation d'une technologie de filtration par membranes. Les résultats ont montré que, par l'implantation de traitement tertiaire, le potentiel d'eutrophisation pouvait être diminué de 50 à 60%, tandis que l'élimination complète de l'effluent à l'aide de membranes réduisait celui-ci de 80% via une élimination de la contribution de l'effluent de l'usine de papier journal à cette catégorie d'impact.

CONCLUSIONS

En conclusion, l'approche proposée permet une interprétation plus informée des résultats d'ACV ayant pour objectif l'indentification d'opportunités d'amélioration environnementale. Par exemple, une comparaison des résultats d'analyse de sensibilité peut montrer comment les résultats de caractérisation sont affectés par l'incertitude sur les paramètres d'arrière-plan et l'analyse de la contribution des paramètres procédé de l'usine permet d'effectuer des recommandations sur les opportunités d'amélioration, non seulement de la performance environnementale, mais aussi de la qualité des données du modèle.

Les bénéfices additionnels de l'approche proposée sont de deux ordres. Premièrement, l'étape de pondération, encore en développement et ajoutant nécessairement des éléments de subjectivité à l'étude, est évitée. Deuxièmement, une technique de sensibilité ne requerrant aucune information sur la distribution probabiliste des données, laquelle est souvent très difficile à obtenir et ce, plus spécifiquement pour les données de la littérature et provenant de bases de données commerciales, est utilisée.

Il est important de noter que l'évaluation de l'incertitude sur les paramètres s'est limitée aux données d'inventaire et n'a pas inclus l'incertitude sur les facteurs de caractérisation puisque l'information nécessaire n'était pas fournie avec les méthodes d'évaluation des impacts. Cependant, si cette information devenait disponible, il serait intéressant d'ajouter ces évaluations à la phase d'interprétation.

D'autre part, l'utilisation d'approches alternatives pour deux choix méthodologiques a été évaluée. Il a été montré que ni l'approche d'imputation pour les opérations de la scierie ni l'exclusion de la cueillette du papier usé n'avait d'influence significative sur les résultats.

Les scénarios développés impliquant une augmentation de la production de pâte recyclée et/ou l'implantation de cogénération ont montré des bénéfices environnementaux significatifs (par exemple, une réduction de 20 à 40% dans le potentiel de réchauffement planétaire), sauf en ce qui concerne certaines catégories d'impact pour lesquelles les résultats de caractérisation ont augmenté en conséquence de l'augmentation de la consommation de gaz naturel générée par les nouvelles configurations. D'autre part, il a été démontré que des bénéfices pouvant être tirés des scénarios orientés énergie dépendaient fortement du mélange d'énergie qui dépend à son tour de l'emplacement de l'usine. Finalement, les scénarios orientés effluent ont montré une amélioration significative relativement au potentiel d'eutrophisation. Cette amélioration était encore plus marquée pour le scénario impliquant l'élimination complète de l'effluent via une technologie de filtration par membranes laquelle enraye la contribution de l'effluent de l'usine de production du papier à cette catégorie d'impact.

Les analyses de scénarios ont été limitées à une modification du modèle de référence afin d'illustrer son utilisation pour l'évaluation d'options de procédé et de démontrer les bénéfices potentiels de stratégies environnementales courantes spécifiques à l'industrie papetière. En conséquence, certains éléments d'une ACV comparative n'ont pas été inclus tels que l'utilisation de technologies marginales et l'ajout de contrôle d'interprétation supplémentaires pour les résultats des scénarios. L'utilisation future du modèle à des fins comparatives devra considérer ces limitations.

Finalement, les résultats et conclusions tirés de cette étude de cas ne sont valides que pour le système étudié. Aucune généralisation ne peut être effectuée due à l'influence significative du modèle de production d'électricité sur les résultats de caractérisation. Des travaux futurs utilisant ce modèle de référence pourront être orientés vers l'analyse d'options de procédés et l'investigation d'applications émergentes de l'ACV, telles que la démonstration de l'amélioration continue, l'évaluation de modifications majeures au procédé et de l'établissement de la configuration de procédé produisant l'impact environnemental minimal.

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LIST OF ABREVIATIONS

ADMT	Air dried metric ton
BOD	Biochemical oxygen demand
CGS	Coated groundwood specialty
COD	Chemical oxygen demand
DALY	Disability adjust lifetime years
DIP	Deink pulping
DQI	Data quality indicators
EPDS	Environmental profile data sheet
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
ONP	Old newspaper
PM	Paper making
SETAC	Society of Environmental Toxicology and Chemistry
TMP	Thermomecanical pulping
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
TSS	Total suspended solids
UCGS	Uncoated groundwood specialty
UNEP	United Nations environmental program
USEPA	US Environmental Protection Agency

LIST OF APPENDICES

PART I - LITERATURE REVIEW

CHAPTER 1 – PROBLEM INTRODUCTION AND CONTEXT

The pulp and paper industry is one of the most important industrial sectors in Canada. In 2001, Canada ranked first in the world with 21.7% of global newsprint production. Approximately 92% of that production was destined for export markets, mainly in the United States, Europe and Japan (Natural Resources Canada 2004).

In the last decade, newsprint mills improved their environmental performance by implementing several new measures. These tactics include the addition of recycled fibre content to their products, the implementation of additional end-of-pipe technologies in order to reduce the organic load from their operations to the receiving water streams, and various energy and water reduction programs (FPAC 2001).

At present, the pulp and paper sector is aiming for continuous environmental improvement. This aspiration is driven by the concerns of the communities around the mills, more stringent regulations, international commitments, the increasing demand for greener products, and the additional economic benefits that can be achieved. Current strategies are oriented towards increasing the content of recycled fibre in newsprint, co-generating electricity inside the mill, and maximizing heat and mass recovery from wastewater streams. However, the environmental assessment of these strategies is generally targeted to the site-specific effects, without considering benefits and impacts during the newsprint life cycle.

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts associated with a product or process during its entire lifetime. Its potential applications include the identification of improvement opportunities, as well as use as a decision-making tool in strategic planning and product or process design (ISO 1997). LCA involves the quantification of inputs from and outputs to the environment for a defined system under study, identifying their origins among different life cycle stages (e.g. raw material extraction, production, use and disposal). These inputs and outputs are then classified and characterized into different impact categories (e.g. global warming, acidification, eco-toxicity) using simplified models.

LCA methodology is presently undergoing a harmonization process performed by the International Standardization Organisation (ISO), the United Nations Environmental Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). Topics that are still under discussion include impact assessment modeling and the interpretation of results in order to draw conclusions. Various guidelines and frameworks are proposed in the literature in order to harmonize these topics, but they are rarely applied in real case studies.

In the pulp and paper sector, the application of LCA for process analysis and comparisons of improvement options has increased in recent years, but there is no evidence that this has occurred at the industry level in Canada (Gaudreault *et al.* 2004). Furthermore, methodological topics still under discussion are generally missing from most of the published case studies.

Newsprint mills can use LCA to identify improvement opportunities over the whole life cycle and to assess process modifications as a result of environmental strategies. Existing approaches for LCA methodological topics still under development can be applied according to the context of the study and its intended use. The consequent benefits can be observed via improved communication with different stakeholders about the effects of process modifications, as well as a better quantification and assessment of the environmental benefits and impacts from process modifications. Finally, LCA can be used as a tool to quantitatively demonstrate continuous environmental improvement from a product chain perspective.

CHAPTER 2 – OVERVIEW OF NEWSPRINT LIFE CYCLE

In this chapter, the newsprint life cycle is presented focusing on the technical aspects of the production phase. Figure 2.1 shows a simplified scheme of the newsprint life cycle.

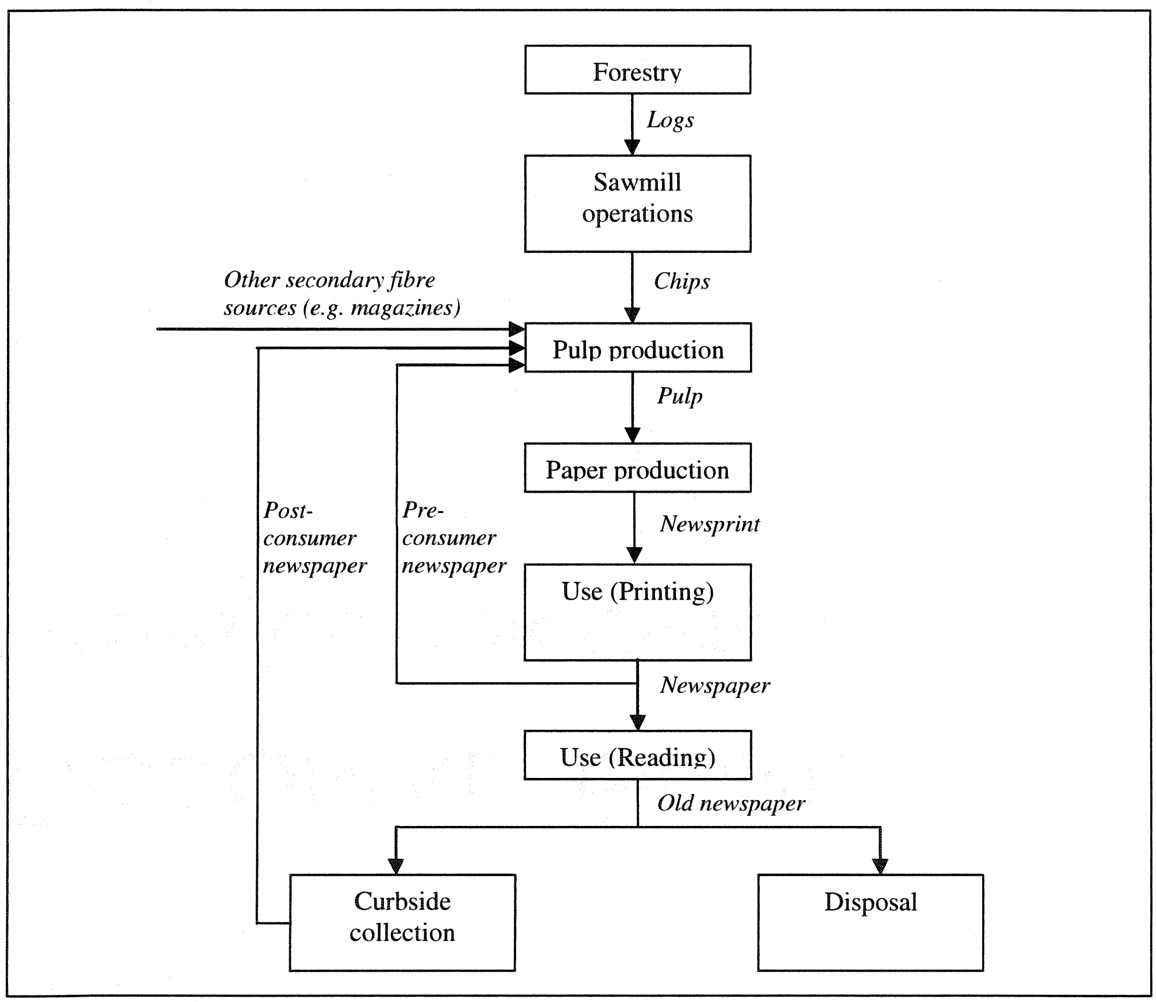

Figure 2.1: Simplified newsprint life cycle

2.1 Forestry

Forestry involves the activities of timber harvesting, other silvicultural activities (e.g. site or seed bed preparation, planting, tending of natural regeneration, pre-commercial and commercial thinning, competition control, fertilization, etc.) and forest management planning.

The main silviculture systems used in Canada are (Canadian Institute of Forestry 2002):

- Clearcutting: The removal of all trees from a stand at one time.
- Seed Tree: The removal of all trees from a stand at one time except for a small number of seed bearing trees.
- Shelterwood: The removal of all trees from a stand in two or more separate harvests.
- Selection: The removal of some trees at regular intervals from a stand, usually from several age or diameter classes, individually or in small groups.

Most managed forestland in Canada is under even-aged management using clearcutting, seed tree, or shelterwood systems. After harvesting, logs are sorted according to species, quality, size, end-use, or destination and sent to sawmills.

2.2 Sawmill Operations

These operations are oriented towards the production of lumber for the construction industry. Chips are the co-products of this process and they constitute the raw material for the pulp and paper industry. Wood waste materials like bark, shavings, and sawdust, known altogether as “hog fuel”, are used as biofuels at the pulp and paper mills.

2.3 Newsprint Production

2.3.1 Thermomechanical Pulping (TMP)

In this process chips are reduced to a fibrous mass (i.e. pulp) by a mechanical separation of the fibers with the application of heat and pressure. Figure 2.2 depicts the process.

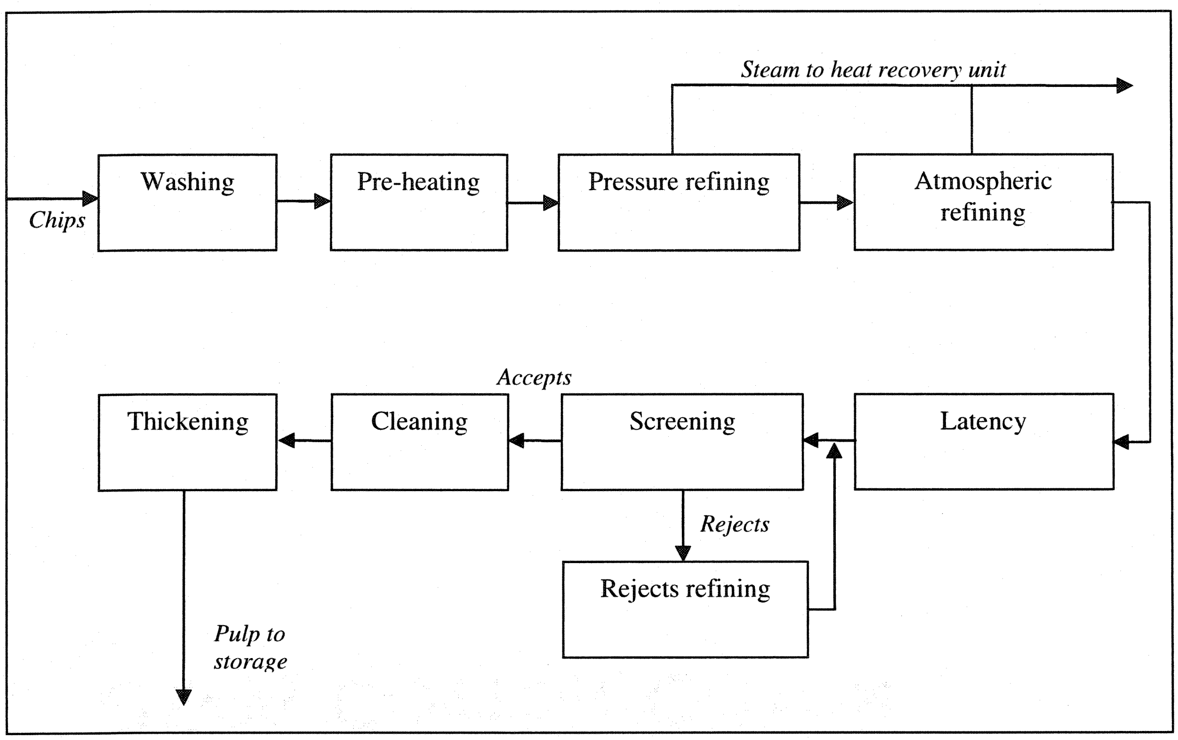

Figure 2.2: Flow diagram of the TMP process

Before entering the process, chips are screened in order to separate the fines and the oversized pieces. The former are usually burned along with the hog fuel to produce steam for the process while the latter are reduced into smaller fractions.

After washing and pre-heating, chips are introduced into the open eye of a disc refiner. As the material moves, chips are progressively broken down into smaller particles and finally into fibers. Water is supplied to the eye of the refiner to control the pulp consistency (i.e. fiber concentration) and sometimes chemicals are also added to aid with this process.

In order to obtain an optimum fiber development, a significant amount of power must be provided to refining. Electric energy consumption is around 6 to 10 MJ/kg pulp (Paris 2002). On the other hand, the high temperature of the TMP process allows for recovery of more than 70% of the energy in a form that is useful in other mill areas (e.g. paper drying).

2.3.2 Deink Pulping (DIP)

Deinking is essentially a cleaning process where the ink is removed from the pulp fibers obtained from wastepaper. Deinking technologies include a washing process, a flotation process and a combination of the two (Smook 1992). The flotation technology is illustrated in Figure 2.3.

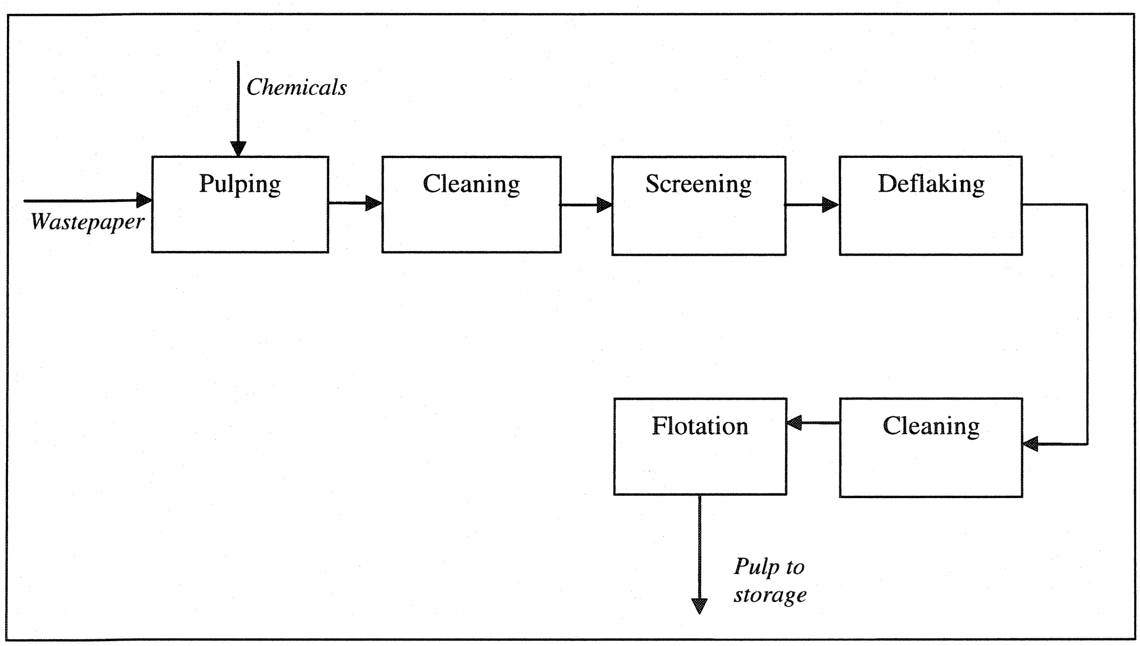

Figure 2.3: Flow diagram of a conventional flotation deinking process

Old newspapers are furnished to the deinking process, and old telephone directories and magazines can also be included in order to add strength to the fiber. The key chemicals used for deinking are surfactants that affect the surface tension of the liquids and solids. Three specific types of surfactants are important in deinking applications (Smook 1992):

- Detergents to remove the ink from the fiber
- Dispersants to keep the ink particles dispersed and prevent re-deposition onto the fibers
- Foaming agents to reduce the surface tension of water and to promote foam formation

Chemicals are introduced during the repulping operation to promote flocculation of the ink particles and the formation of foam. In the floatation cell, air bubbles are introduced to the stock in order to attract ink and dirt particles, causing them to rise to the surface of the cell where they are removed.

Due to the amount of contaminants in the wastepaper stocks, including dirt, tramp metal, adhesives, coatings, resins and ink, a significant amount of sludge is generated in this process. For news grades, 8 to 15% of the stock is rejected. The management of DIP sludge includes landfilling, drying plus landfilling, incineration, composting, wet oxidation, and use as a fertilizer or in building materials (Doris 2002).

2.3.3 Paper Making

The objectives of this process are water extraction and the formation of a paper sheet with defined properties. Figure 2.4 illustrates the process and indicates the consistency in each of the stages.

In the first section of the paper machine, a large amount of water is extracted and a fiber web is formed. This web is then conveyed through a series of roll presses where additional water is removed and the web structure is consolidated. Finally, the web is dried by evaporation of the residual water to produce the paper sheet. The drying process is the most energy intensive section of the paper machine.

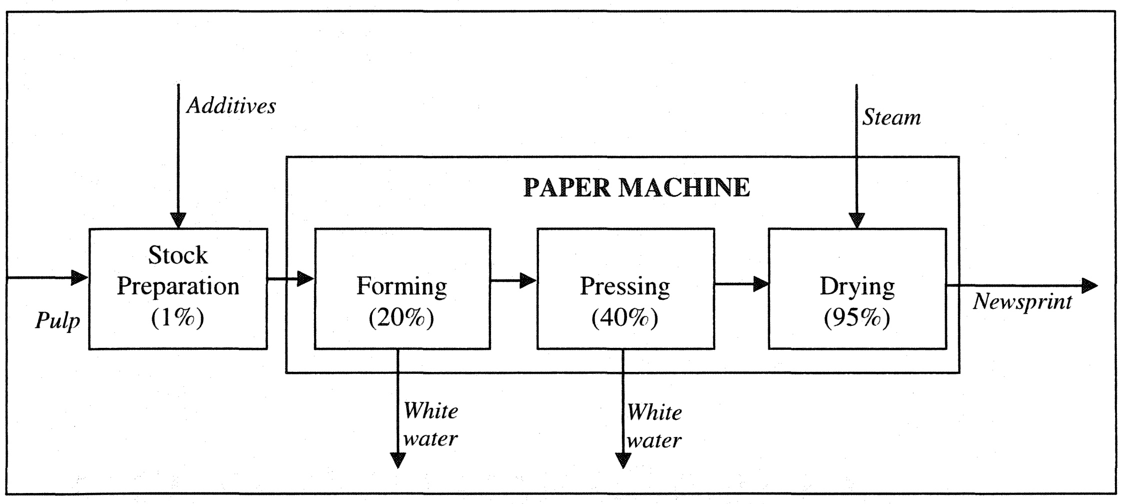

Figure 2.4: Flow diagram of the paper making process

White water is the drainage from wet stock. Its temperature ranges from 50 to 55°C. White waters are classified as rich or lean depending on their fiber content. The rich white waters are collected and immediately recirculated. Only the leanest water is removed from the system and it is first taken to a fiber recovery unit. White waters are used in the paper machine showers, press section, vacuum, and cooling systems. The modern trend is toward greater "closure" of the white water system in order to reduce the fresh water introduced into the process (Smook 1992).

Recycled pulps have distinctly different characteristics when compared to virgin pulps. Regardless of how they have been processed, they always contain some residual contamination that tends to build up in the system and precipitate or agglomerate at some point during the paper making process.

After drying, the newsprint sheet is calendered or pressed with a roll in order to reduce thickness, then collected in a specific diameter reel and finally cut and winded into rolls. These rolls are wrapped and sent to the customer.

2.3.4 Mill Utilities

a. Industrial Water Treatment

Usually raw water is treated in order to remove impurities that would otherwise adversely affect newsprint quality or increase maintenance costs. Depending on the particular quality requirements, any of the following processes are commonly employed (Smook 1992):

- Settling or sedimentation
- Filtering
- Coagulation followed by sedimentation or filtering

Other processes may be employed depending on specific requirements (e.g. boiler feedwater). Supplemental processes include chlorination or ozonation, aeration, de-aeration, demineralization (ion exchange), and fine filtration.

b. Steam Generation

Steam necessary for newsprint production is usually generated on-site by a boiler system. Generated steam can also be converted into electrical energy by means of a turbine. According to its design, a boiler furnace can burn solid, liquid or gaseous fuels including coal, hog fuel, sludge, oil, and natural gas.

c. Electrical Distribution

The electrical power utilized in newsprint mill operations is typically a combination of purchased power from the grid and self-generated power from hydro and thermal facilities.

2.3.5 Residuals Management

a. Effluent Treatment

Effluent treatment is usually carried out by means of sedimentation to remove suspended solids (primary treatment) and biological oxidation to remove BOD (secondary treatment). Any treatment beyond primary and secondary treatment is usually termed "tertiary treatment".

- **Primary Treatment**

This term generally refers to the removal of suspended solids from mill effluents (primary sludges). In the pulp and paper industry, solids removal is always accompanied by some BOD reduction. Screening is often used as a preliminary step to remove relatively large floating or suspended particles from an effluent stream.

The two principal methods of primary treatment employed in the pulp and paper industry are gravity sedimentation and dissolved air flotation. Sedimentation is by far the most common process because it is relatively insensitive to variations in flow and solids concentrations and requires little attention and maintenance (Smook 1992).

- **Secondary Treatment**

Aerobic biological treatment is the most typical secondary treatment technology in the pulp and paper industry. Aeration lagoons, activated sludge, and biological filters are the available options. However, the activated sludge system is the most popular high-rate method of treatment (Smook 1992). In this process, clarified wastewater is fed continuously to an aeration tank and the microorganisms in the activated sludge metabolize the dissolved organic waste. Effluent is continuously drawn off to a secondary clarification unit where the solids are separated. A certain portion of these solids is recirculated back to the aeration tank to provide a high floc density, while the remainder constitutes solid waste known as secondary sludge.

- **Tertiary Treatment**

The objective of tertiary treatment technologies is to remove pollutants that are not eliminated during secondary treatment, such as residual COD, nutrients, or suspended solids. Due to its high quality, it is possible to re-use the effluent from tertiary treatment in the paper making process as a substitute for fresh water or to achieve lower discharge loads to the receiving water bodies.

Chemical precipitation is a common form of tertiary treatment that can be a complement to biological treatment when it is desirable to achieve lower emissions of organic substances. Chemical precipitation involves the addition of chemicals to the wastewater to facilitate the removal of solids by sedimentation or flotation. Thus, suspended and colloidal matters are separated, including nitrogen and phosphorus. The precipitation of TSS and nutrients with inorganic chemicals produces a considerable quantity of sludge that is difficult to dewater and is often landfilled.

Tertiary dissolved air flotation aided by chemical coagulation and flocculation with alum and polymer is being applied in a TMP-DIP newsprint mill in Sweden in order to reduce COD and phosphorous discharges (Thoren *et al.* 1997).

Membrane technologies, depending on the applicable membrane cut-off size and the filtering pressure, can theoretically remove almost 100% of the organic material. High-pressure filtration methods produce cleaner water, but consume more electricity and must be equipped with more efficient pre-treatment or countermeasures to protect against plugging. The concentrate can be sent to biological treatment or may require further concentration into a solid fuel for disposal by incineration. The quality of the filtrate can be sufficient to replace most of the fresh water used in the process. Investigations on how to use permeate to replace fresh water and whether to treat the concentrate separately are ongoing (IPPC 2001).

b. Sludge Handling

Primary and secondary sludges as well as the DIP sludges must be de-watered before final disposal, whether by landfill, soil application or incineration. Dewatering is carried out by means of wire or screw presses. In a typical dewatering operation, sludges can achieve 40-45% solids (Smook 1992).

The potential benefits of sludge dewatering are:

- Reduced volume and transportation costs
- Easier handling
- Reduced environmental impact when landfilling
- Improved heat value when incinerating.

Generally, primary sludges are relatively easy to dewater, while biological sludges are extremely difficult. Polymer additives are added as aids in flocculating and dewatering.

c. Solid Waste Disposal

Solid wastes from newsprint production processes include:

- Fiber rejects from TMP
- Secondary fiber contaminants rejected from DIP
- DIP sludges
- Ashes from steam generation
- Sludge from wastewater treatment

TMP rejects are usually burned in the boilers. DIP rejects have no recycling potential and their incineration is difficult due to potential emission and corrosion problems. While ashes can be used as a resource for building materials, the viability of that option depends on the market demand. Therefore DIP rejects and ashes are usually landfilled. For DIP and wastewater sludges, which together consist of the biggest waste fraction, there are some alternatives to disposal by landfilling, such as on-site or off-site incineration and soil application. Usually, the only benefit to on-site incineration is a reduction in the volume of sludge to be disposed, since generally little heat value is realized from burning the sludge. Furthermore, the mixture of sludge with hog fuel has a negative impact on steam generating capacity. Off-site incineration can be carried out in cement kilns, where the sludges can be further dried with waste heat from the cement kiln and the ash can remain in the product (cement). However, the feasibility of this alternative can be limited by the distance between the newsprint mill and the cement kiln.

Soil application of sludge includes uses for agriculture, silviculture, horticulture and reclamation of degraded sites. Negative environmental effects of DIP and wastewater treatment sludges on soil and water quality have not been observed (Trepanier *et al.* 1998; Graydon *et al.* 1999). In the Province of Quebec, the application of this technique has increased considerably in recent years (Leclerc *et al.* 1998).

2.3.6 Supply and Distribution Systems

a. Virgin Fiber Supply

Logs are harvested during the winter season and usually transported by trucks to sawmills where they are stored. Chips and hog fuel are also transported from sawmills to the newsprint mills by truck. However, a given sawmill will not typically supply both chips and hog fuel to the newsprint mill. Because hog fuel is a waste, newsprint mills only pay for its transportation, and sawmills try to get permanent supply contracts with big co-generation facilities. Therefore, suppliers will be elected based on minimum distance and hog fuel availability.

b. Secondary Fiber Supply

Secondary fiber or wastepaper sources are classified as pre-consumer and post-consumer. Pre-consumer sources are converting or printing plants where wastepaper, in the form of cull rolls, clippings, off-quality products, or over-issue, is generally clean and well sorted. Post-consumer sources are homes, offices, and retail outlets from which the waste must be collected, sorted and baled. Wastepaper from post-consumer sources is considered less desirable because it is relatively less sorted and higher in contamination (Smook 1992).

Post-consumer wastepaper suppliers are usually located in areas of high population density, where a dependable supply of waste material can be more easily collected and transported. Thus, municipal governments are usually involved in controlling the flow of wastepaper into the mills. In many instances, the wastepaper dealer is bypassed as the municipality sorts, bales, and sells wastepaper directly to the mills.

Since Canada has a relatively small population compared to the United States and because most of its newsprint production is exported, newsprint mills are required to import old newspaper to meet their needs. Approximately 55% of the secondary fiber comes from Canadian sources; the balance is imported primarily from the United States (FPAC 2003b). Secondary fiber from Canadian sources is transported by truck whereas that from the United States is mostly transported by rail.

c. Newsprint Distribution

Most newsprint produced in Canada is exported. In 2002, approximately 87% of newsprint production was distributed to more than 70 countries (Natural Resources

Canada 2004). Around 70% of the pulp and paper products are exported to the United States, 10% to the European Union and 10% to Asia (Industry Canada 2003).

2.3.7 Integrated Operations

The integration of forest products manufacturing operations ensures optimum economic utilization of available timber resources. The optimum economic impact is achieved when wood handling and associated plants are integrated at a single location (Smook 1992).

The coordination of services (e.g., water supply, steam, power, effluent treatment, etc.) can result in a more efficient use of resources and lower emissions to the environment. For instance, the integration of sawmills with pulp production facilitates optimal utilization of hog fuel. Further integration with paper making reduces steam and water consumption, since these streams can be recirculated from the pulp unit and the paper machine, respectively. In addition, transportation distances can be reduced as well. Paper manufacturing mills in Canada tend to integrate the production of pulp and paper at the same site (Natural Resources Canada 2004).

2.4 Newsprint Use

Newsprint is basically used to print daily and weekly newspapers. The other major uses are inserts, flyers, newspaper supplements, and directories.

The printing industry is the largest collective consumer of newsprint. Of the available pressing techniques, the most commonly used for newspaper are the lithographic and flexographic methods. The latter produces less quality than the former, but it offers a better compatibility with deinking process.

Generally, pressrooms have found that recycled newsprint is not significantly different with respect to runability. Rather, differences in printability and appearance are more apparent. Recycled sheets tend to be more absorbent because of higher sheet porosity; therefore, more ink is required in printing (Smook 1992).

2.5 Newspaper Disposal and Recycling

Landfill sites are becoming increasingly difficult to find and more costly to operate. Newsprint recycling is an alternative encouraged by governmental legislation, which seeks to reduce landfill loadings and to lessen dependency on forest resources by mandating a minimum secondary fiber content level for newsprint.

Two primary indices are used to measure the level of recycling. The recovery rate is the amount of wastepaper recovered for reuse compared with paper consumed. The utilization rate is the amount of secondary fiber used in paper/board production compared with the total fiber used. The average recovery rate in Canada is around 40% (Recycling Council Ontario 2003) while the utilization rate is about 20% (FPAC 2003a). Recovered paper is collected at the curbside, from office buildings, retail stores and other locations. It is then transported to a processing facility or directly to recycling mills. Laboratory tests indicate paper fibers can be recycled up to seven times before becoming too short to make paper.

Other disposal alternatives for newspapers that are not currently applied in Canada are incineration and composting. Composting, however, has increasingly been proposed as a practical and environmentally efficient alternative to landfills. It is also perceived as a form of recycling, since it is essentially a way of returning organic matter and nutrients originally harvested from the land base. There are numerous studies that demonstrate the value of paper compost as a horticultural growing mix (RCO 2003).

CHAPTER 3 – CRITICAL ENVIRONMENTAL ISSUES FOR INTEGRATED NEWSPRINT MILLS IN CANADA

3.1 Environmental Discharges

3.1.1 Water Discharges

The major sources of effluent discharges in an integrated newsprint mill are the following (Smook 1992):

- Water use in wood handling and chip washing
- White waters from screening, cleaning and thickening
- Paper machine white water
- Fibre and liquor spills from all sections

Three major categories of water discharges are effluent solids, organic and nutrient load and toxicity.

Entrapment of fibres or other suspended solids in the gill tissue of fish can cause stress, secondary infection and possibly suffocation. Bottom accumulation of organic material in natural systems leads to rapid oxygen depletion in water bodies, causing the aerobic aquatic organisms to die off. Biochemical Oxygen Demand (BOD) refers to the amount of oxygen required by microorganisms to break down wood fibers and other components of effluent. Total Suspended Solids (TSS) refers to the amount of fiber in the effluent. These are both important indicators because the higher the level of TSS and BOD, the less oxygen is available for other aquatic life.

In Canada, abatement efforts in the past have been generally focused on the reduction of TSS and BOD. Between 1989 and 1999, the BOD of mill effluents was reduced by 94%. Over the same period, TSS were reduced by over 70%. During this time, most of the pulp and paper mills implemented biological treatment technologies for their wastewater treatment (FPAC 2001). However, a secondary effect of biological treatment is the nutrient load due to the phosphorus and nitrogen usually added to the biological treatment plant to maintain the necessary balance of C: P: N for the growth of active biomass. Fortunately, typical newsprint mill wastes are weakly toxic by conventional measurement, and are usually essentially non-toxic following biological treatment.

The impact of pulp and paper mill effluents is being evaluated on the benthic and fish populations through the Environmental Effect Monitoring Program. On a national scale, a mild to moderate eutrophication response pattern on the benthic invertebrate community has been observed, likely due to the phosphorus, nitrogen, and organic content of the effluent. The effects observed on fish downstream of pulp and paper mill effluents reveal a combined response pattern of metabolic disruption and nutrient enrichment. Furthermore, the combined metabolic disruption/nutrient enrichment observed in fish reflects the eutrophication results seen in benthos. However, more monitoring will be carried out in order to assess the spatial extent and ecological importance of these observed effects (Environment Canada 2003).

Currently, abatement measurements are strongly related to the recovery and recycling of process water in order to reduce fresh water consumption. Increased process water closure will result in smaller and more concentrated discharges, which in general can be treated more efficiently (IPPC 2001).

3.1.2 Air Discharges

Air quality is a vital environmental consideration because of the health risks associated with air emissions, especially for the young, the elderly, and individuals with respiratory difficulties.

The main sources of air emissions in integrated newsprint mills are the following:

a. Combustion gases from steam generation

These include CO_2, CO, NO_X, SO_2 and particulates. The amount of released gases depends on the kind of fuel used, the air abatement applied, and the amount of steam consumed in the process.

To decrease these air emissions, several measures are available, including cogeneration of heat and power, installation of low NO_X technology or electrostatic precipitators of particles in the boilers, use of low sulphur fuel, and use of renewable sources of energy (e.g. hog fuel) in order to reduce the emissions of fossil CO_2.

b. Volatile organic compounds (VOC) from TMP

Due to the high temperature involved in chip refining, some of the volatile wood compounds are evaporated during this process. VOC emissions are usually recovered in the heat recovery unit, but in cases where wood species with high extractive content are used, collection and further treatment are applied.

3.2 Environmental Regulations

Federally, pulp and paper mills are subject to the general pollution control provisions of the Fisheries Act and the Effluent Regulations promulgated under the Act. In addition, each of the provinces has its own environmental legislation. For air pollution control, the provinces have almost exclusive responsibility and authority.

The Pulp and Paper Effluent Regulations (PPER) under the Fisheries Act set discharge limits for TSS and BOD and prohibit the discharge of effluent that is acutely lethal to rainbow trout. PPER include as well a requirement for an Environmental Effects Monitoring (EEM) program in order to demonstrate whether or not the major improvements in wastewater treatment processes were associated with similar improvements in the receiving environment, and to evaluate the long-term effects of pulp and paper mill effluents on Canadian aquatic ecosystems (Environment Canada 2003).

3.3 Environmental Strategies for Integrated Newsprint Mills

3.3.1 Additional DIP Production

Sustainability of forest resources is a current environmental concern of the pulp and paper industry as a sector supporting the UN Convention on Biological Diversity in order to preserve wild species and habitat. One way to conserve forest resources is to recycle wastepaper. Furthermore, additional environmental benefits can be achieved from wastepaper recycling, such as reductions in the amount of wastepaper being landfilled and decreases in electricity consumption, since the recycling process is less energy intensive than paper production from virgin fibre.

Since 1990, the Canadian industry has invested almost $2 billion to build de-inking facilities and to improve the screening processes to enable the mills to use recovered papers. During this time, the recycling capacity has doubled in Canada and the industry's electricity consumption has been reduced by over 2.5 million megawatt hours per year (FPAC 2001).

However, there are still a number of constraints for wastepaper recycling such as (Doris 2002):

- Availability of secondary fibre
- Variable quality of post-consumer grades
- Variable composition of fibres, inks and coatings
- Deterioration of optical properties
- Runnability problems at the paper machine
- Sludge disposal problems

3.3.2 Process Closure

Newsprint mills have the most integrated white water systems. Fresh water is mainly used for the dilution of chemical additives, the cooling and sealing systems, and at locations of the paper machine where high quality solid-free water is necessary.

Canadian pulp and paper mills have slashed their water consumption per tonne of output by 30% since 1990 (FPAC 2001). The use of water at pulp and paper mills has dropped dramatically as mills have sought technologies and processes to progressively close the system.

Closing up the process water system offers both advantages and disadvantages. Enhanced water system closure leads to a considerable loading of the process water with colloidal and dissolved organic and inorganic compounds, which may cause serious problems in the production process if no control measures to avoid possible drawbacks are undertaken. Some of the advantages and disadvantages of water system closure are (IPPC 2001):

- Advantages:
    - Less water consumption
    - Less wastewater discharge
    - Production increase not hindered by end-of-pipe treatment
    - Decrease in fibre losses
    - Elevated process temperature that improves paper web dewatering
    - Reduced energy demand

- Disadvantages:
    - Build-up of (suspended) solids
    - Build-up of organic and inorganic substances
    - Corrosion problems

- Increasing use of additives
- Clogging of equipment
- Product quality related problems

In TMP/DIP integrated newsprint mills, the degree of water system closure attainable is limited by the high standard in paper properties that must be achieved (e.g. brightness).

3.3.3 Co-generation of Heat and Power

The energy use issue is strongly related with the climate change problem. Pulp and paper is a high-energy consuming industry and it has been identified by the Federal Government as one of the large final emitters targeted in its Climate Change Action Plan.

The target set for these sectors is to achieve a 15% reduction from "business as usual" forecast emissions for 2010, or 301 kg CO2e/tonne of product in the case of the pulp and paper industry (Lansbergen 2004).

Cogeneration is an alternative to increase the overall energy efficiency of the newsprint production process. By this technique, steam is produced to generate electricity and, at the same time, excess heat is reused to cover the mill's needs. It should be noted that the achievable improvements depend on the energy system to be replaced. The main constraints in the implementation of cogeneration in Canada are biomass availability and the scope of the Climate Change Policy.

The total surplus of wood residuals available for use (not necessarily economically available) could replace only 40% of the current electricity purchases. On the other hand, the climate change policy only considers direct emissions from stationary combustion sources and it does not allow offsetting the direct emissions by the displaced emissions within a provincial grid. Installing a cogeneration unit to reduce electricity purchases increases the mill's direct emissions and if the cogeneration unit is fossil fuel-fired, the increase will be significant and perhaps prohibitive (Lansbergen 2004).

CHAPTER 4 – OVERVIEW OF LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

LCA is a method to assess the potential environmental impacts associated with a product, process or service along its entire life from resource extraction to ultimate disposal.

The potential applications of LCA include (ISO 1997):

- Identification of improvement opportunities for environmental aspects
- Decision-making tool in strategic planning, priorities definition, and product or process design
- Selection and evaluation of relevant environmental performance indicators
- Marketing programs (e.g. eco-labelling)

4.1 General Methodology

LCA methodology involves the following four phases:

- Goal and scope definition
- Inventory analysis (LCI)
- Impact assessment (LCIA)
- Interpretation

Figure 4.1 shows the relationship between these four phases and general LCA applications (ISO 1997). The double arrows illustrate the iterative nature of the methodology.

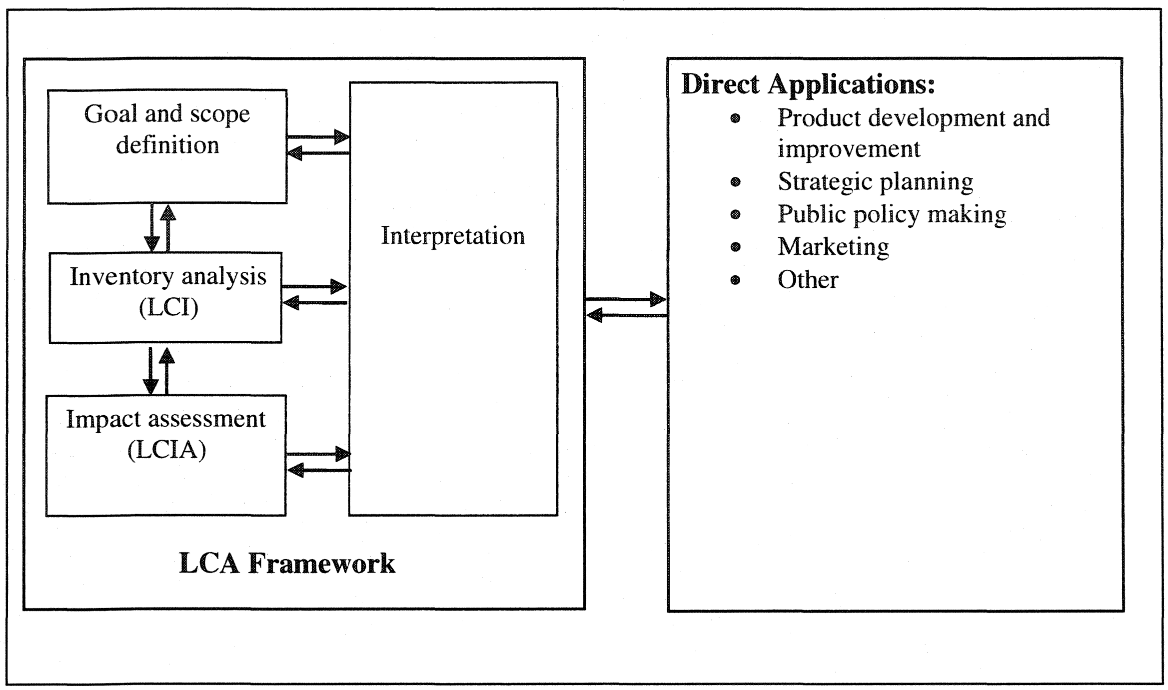

Figure 4.1: Phases of LCA according to ISO 14040

4.1.1 Goal and Scope Definition

The goal defines the purpose of the study as well as its intended application. The scope defines the extent of the study and it contains a description of the system. Based on the goal of the study, the following methodological choices are defined during the scoping phase:

a. Function and Functional Unit

The functional unit is a measure of the system function, and its primary purpose is to establish a reference to relate the input and output data (ISO 1999). For instance, if the objective of the study is to compare paper towels with hand dryers, the function of these products is to dry hands, and the functional unit can be defined as x pairs of dried hands.

b. System Boundaries

These determine which processes will be modeled and included in the study and with which level of detail. ISO recommends including all the life cycle stages from the resource extraction (cradle) to the product disposal (grave), but excluding those processes or data that will not change significantly the general conclusions of the study (ISO 1999).

c. Data Categories

These define the kind of data necessary for the study. They can be collected at the production sites (i.e. primary data) or obtained or calculated from published references or databases (i.e. secondary data). ISO recommends the use of primary data for those processes that contribute most of the mass and energy flows, or for processes with significant environmental emissions (ISO 1999).

4.1.2 Inventory Analysis

This consists of data collection and analysis. Data on the environmental interventions or stressors (e.g. emissions, resource usage) related to each process included in the study are collected and processed in order to calculate an inventory of environmental interventions per functional unit (e.g. SO_2 per ton of product).

The inventory calculation is not always straightforward because in practice, most of the industrial processes result in more than one product, and intermediate or final products are recycled as raw materials. Therefore, decisions must be made about how to allocate environmental burdens to each output.

ISO recommends avoiding, when possible, allocation and extension of the system boundaries in order to include the secondary functions of the system associated with co-products. When allocation cannot be avoided, it is recommended to allocate the

environmental burdens based on physical relationships among the co-products, reflecting the interdependence of processes and their products. When physical relationships cannot be clearly established, economic ones can be used. When there are outputs that can be categorized partially as co-products and partially as wastes, the environmental burdens can be allocated only to the co-products (ISO 1999).
For example, for wood-based products the following allocation rules are recommended (Jungmeier *et al.* 2002b):

- Forestry: Mass or volume
- Sawmill: Mass or volume and market price
- Wood industry: Mass and market price

Outputs of low value (e.g. hog fuel from sawmill operations) can be considered as co-products of the wood processing industries, if the structure of the acquiring industrial sector depends on these outflows and would otherwise have to substitute them with virgin materials. In these cases, the ISO recommendation about not allocating environmental burdens to this type of co-product must be analysed based on the goal and scope of the study (Jungemeier *et al.* 2002a).

4.1.3 Impact Assessment

This serves to evaluate the significance of the environmental interventions calculated in the inventory analysis. Its purpose is to determine the relative importance of each environmental intervention and to aggregate them to a small set of indicators or impact categories.

According to ISO, LCIA consists of mandatory and optional elements as described in Figure 4.2 (ISO 2001a).

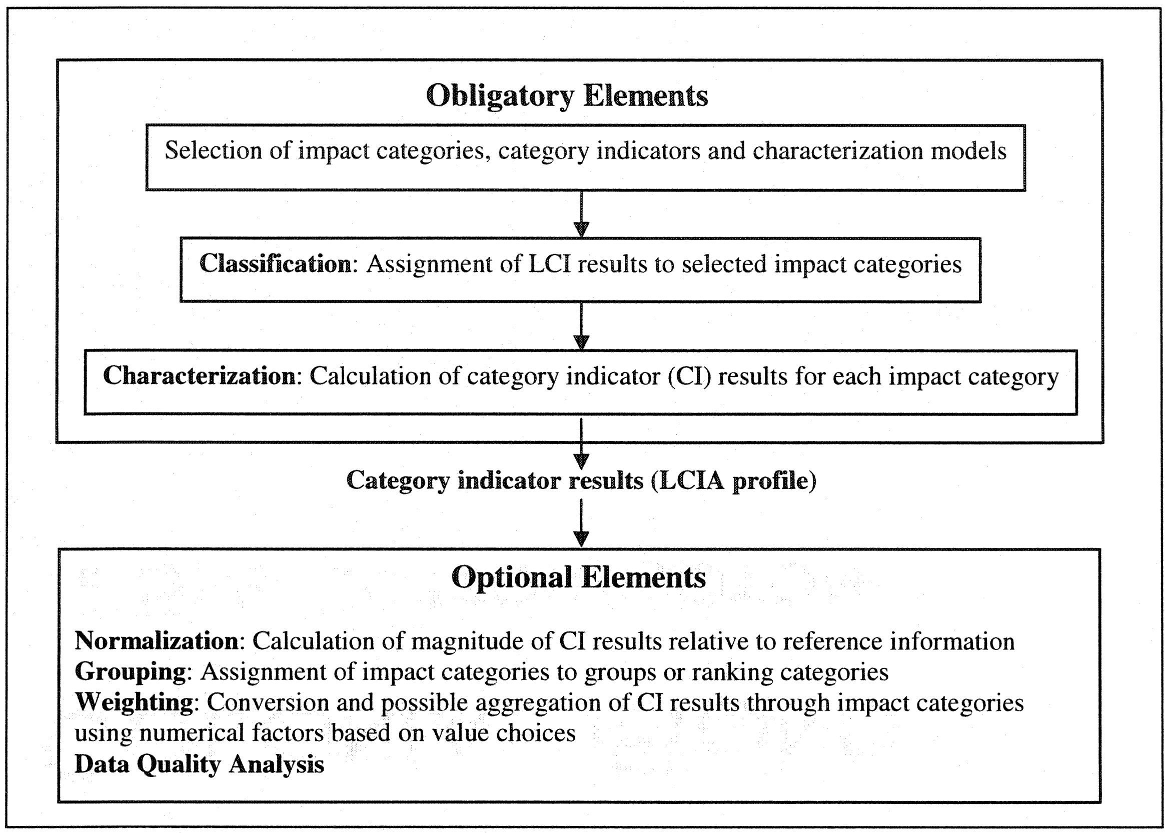

Figure 4.2: Elements of LCIA phase according to ISO 14042

Figure 4.3 illustrates the impact assessment methodology applied to green house gases (GHG) per ton of product (i.e. functional unit for the example).

Impact category	Climate change
Category indicator	Radiative forcing (W/m^2)
Characterization model	IPCC (International Panel of Climate Change) model
Characterization factor	Global warming potential (kg CO_{2eq}/kg GHG)

LCI results:
x kg CO_2 / ton product
y kg CH_4 / ton product
z kg N_2O / ton product

X

Characterization factors:
1 kg CO_{2eq} / kg CO_2
24 kg CO_{2eq} / kg CH_4
296 kg CO_{2eq} / kg N_2O

=

CI results for Climate Change:
(x+24y+296z)
CO_{2eq} / ton product

Figure 4.3: Example of LCIA methodology

a. Issues Related to the Selection of Impact Categories, Category Indicators and Characterization Models

- **Midpoint and Endpoint Indicators**

Category endpoints are variables that are of direct social concern, such as human life span, natural resources, valuable ecosystems or species, etc. Modeling the environmental impacts using these kinds of indicators is also called the "damage approach". Category midpoints are variables in the environmental mechanism between the environmental interventions and the category endpoints, like the concentration of toxic substances, the deposition of acidifying substances, etc. Modeling the environmental impacts using these kinds of indicators is also called the "problem approach" (Udo de Haes et al. 1999a). According to ISO, the category indicator can be defined at any point of the environmental mechanism (ISO 2001a). Figure 4.4 illustrates these concepts with the example of climate change impact category.

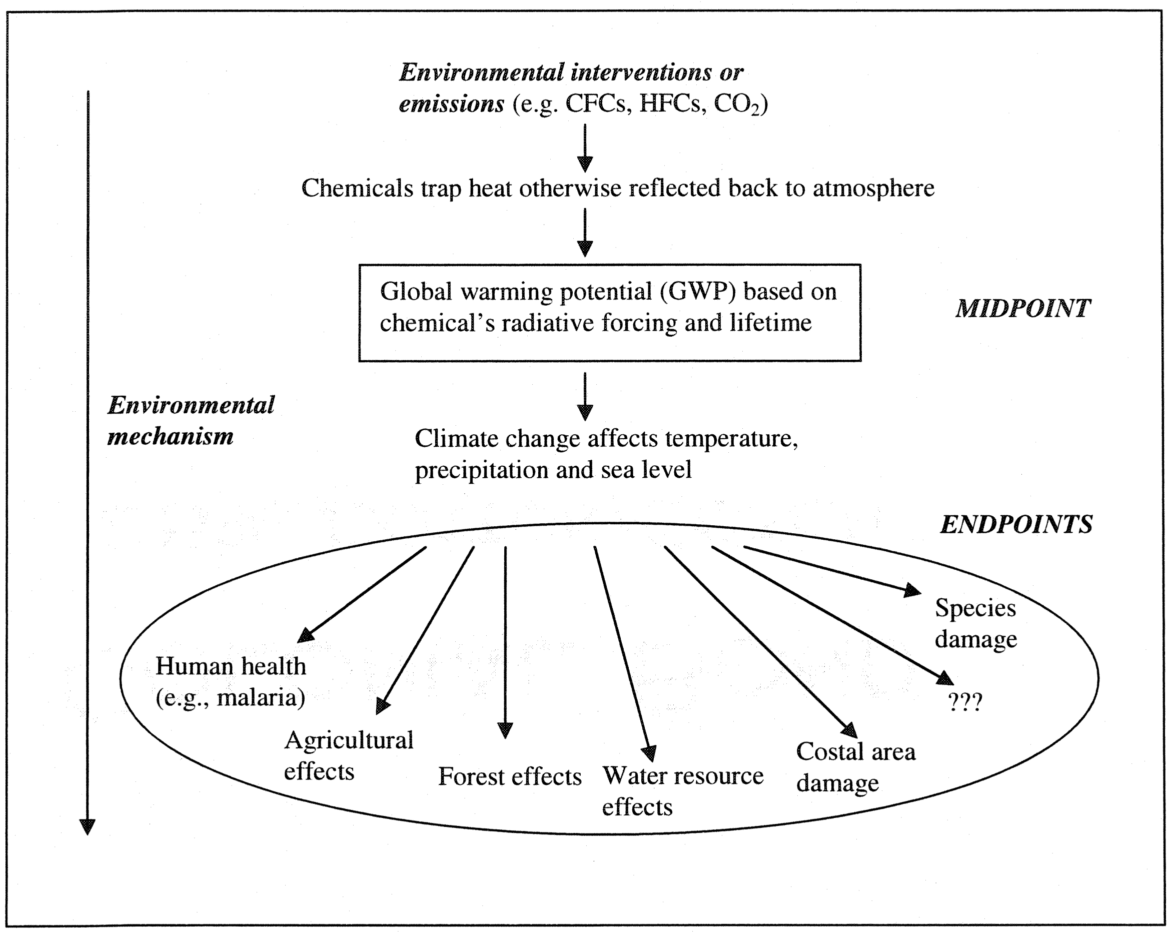

Figure 4.4: Climate change chain of potential impacts (Bare et al. 2003)

Both levels of indicators have complementary merits and limitations (Bare *et al.* 2000). The choice of midpoint or endpoint level involves mainly a compromise between uncertainty and environmental relevance. In general, the definition of an indicator closer to the environmental interventions will result in more certain modeling, but will render the indicator less environmentally relevant. In contrast, definition closer to the endpoints will make the indicator more environmentally relevant, but will render it less certain in its relationship to the environmental interventions (Bare *et al.* 2000; Udo de Haes *et al.* 1999a).

Furthermore, if optional elements based on values (i.e. weighting) will be included in the study, the choice of the endpoint level can be more convenient for the definition of weighting factors since these variables are of direct societal concern. On the other hand, some endpoint indicators are not regarded as being scientifically valid because of the value choices involved in their calculation (e.g. Acceptable Daily Intakes or Reference Doses based on safety factors) (Bare *et al.* 2000; Udo de Haes *et al.* 1999b).

When there is large uncertainty about the endpoint level effects (e.g. some unpredictable consequences of climate change), the suggested approach is to retain the model at midpoint level and use additional evidence introduced by the endpoint modeling to support the evaluation of the importance of different impact categories (i.e. weighting) (Hertwich *et al.* 2001).

- **General Approach of Characterization Modeling**

Disregarding of Temporal and Spatial Differentiation

LCA characterization models commonly disregard spatial and temporal differences in the effects of the environmental interventions. Figure 4.3 illustrated how the characterization factors are applied to LCI results aggregated per functional unit, without making any distinction as to the place or time they were emitted.

Spatial differentiation basically concerns the regional and local impacts that show significant variation in the results when using site dependent approaches (Bare *et al.* 2003; Norris 2003; Ross *et al.* 2002; Krewitt *et al.* 2001; Moriguchi *et al.* 2000; Spadaro *et al.* 1999; Krewitt *et al.* 1998). However, the inclusion of spatial differentiation remains complicated by the lack of spatial distinction in inventory data and characterization factors (Udo de Haes *et al.* 1999a).

The integration over time implies that all impacts, irrespective of the moment that they occur, are equally included. The influence of this assumption is more difficult to capture in LCIA than the influence of site dependent parameters. Furthermore, the allocation of emissions to specific years might be problematic (Krewitt *et al.*, 2001). The alternatives include approximating infinite time by a given time period or attaching a lower weight to events in the far future (i.e. discounting). The recommended practice is to use characterization factors for infinite time without discounting. Infinity can be approximated by a designated long period of time, e.g. 500 years for climate change (Udo de Haes *et al.*, 1999a).

Linearity

LCA characterization results are calculated as the linear product of inventory results and characterization factors. However, the magnitude of the characterization factors may be linked to potential non-linearities in fate and exposure as well as in dose-response characteristics, making them dependent on the background concentration of a given substance (Udo de Haes *et al.* 1999a).

Generally, midpoint indicators are linear by nature because no further specification of the environmental process, or of the dose-response characteristics of the exposed receptor organisms, is taken into account. Furthermore, when indicators are obtained as a quotient between a given predicted concentration and some reference concentration, the characterization factors are independent from the dose or concentration levels of the respective substances (Udo de Haes *et al.*, 1999a).

- **Best Available Practice for the Selection of Impact Categories and Category Indicators**

Current best available practice divides the environmental impact categories into input related categories (i.e. significance assessment of use of resources) and output related categories (i.e. significance assessment of emissions).

Input Related Categories

These include abiotic and biotic resources that are transferred from nature to human-controlled processes and land areas that are occupied by such processes. The underlying assessment framework for these impact categories is not yet adequately stabilized, therefore best available methods have not been yet identified (Udo de Haes *et al.* 2002).

For extraction of abiotic resources, three subcategories are usually distinguished, namely those related to deposits (e.g., fossil fuels and mineral ores), funds (e.g., groundwater, sand, and clay), and flows (e.g., solar energy, wind, and surface water). The concern related to the consumption of such resources is their decreasing availability for future generations. Characterization models have been developed so far for deposits. However, there is still discussion about the aggregation of indicators for resources used for different purposes that are therefore not equivalent (Brentrup *et al.* 2002; Van Oers *et al.* 2002). There is also uncertainty about the figures used in different assessment methods such as total and proven reserves (Van Oers *et al.* 2002) and the future energetic surplus required for their extraction (Bare *et al.* 2003). Despite the fact that impacts of surface water extraction are not being modeled at this time, it has been suggested that possible category indicators such as water use, consumption, and depletion be employed in order to assess water resources from a sustainability perspective (Owens 2002).

For extraction of biotic resources, it is necessary first of all to identify the origin of the species during the inventory analysis in order to ensure the appropriate environmental assessment (i.e. nature or man-controlled cultures). If the organisms are produced in man-controlled cultures, they are not being depleted in nature and their populations may even increase. Category indicators for biotic resources extraction are based on figures like annual use of species, annual replenishment, and current stocks of species. Since necessary data is available only for a limited number of species, it has been proposed that a list of one hundred fish species and precious woods, which have substantial importance as global resources and are classified as vulnerable, endangered, or critically endangered, be included as a minimum list of species in LCA studies (Udo de Haes *et al.* 2002).

Land use impacts (e.g. agricultural production, mineral extraction, human settlements, etc.) are often not included in LCA studies because of a lack of adequate impact indicators. Current approaches aim at a single or limited number of indices because of data availability reasons, including ecosystem productivity and biodiversity (Weidema 2001; Lindeijer *et al.* 2002). However, there is still a lack of inventory-related data to operationalize indicators and a lack of acceptance of the present indicators and modeling proposals (Lindeijer 1999).

Output Related Categories

The output related impact categories can be generally divided into global, regional and local impacts.

Global impacts include climate change and ozone depletion. For these impacts, the following mid-point indicators are recommended: global warming potentials developed by the International Panel on Climate Change (IPCC) and ozone depletion potentials developed by the World Meteorological Organization. However, values are involved in the choice of the time horizon (Udo de Haes *et al.* 1999c). The 100-year time horizon is recommended by the IPCC for climate change (Bare *et al.* 2003).

Regional impacts include acidification, eutrophication, and photochemical smog. The best available practice for regional impacts is to model them at midpoint level. The recommended indicators are: proton release for acidification, stoichiometric sum or macro-nutrients for eutrophication, and Maximum Incremental Reactivity (MIRs) for photochemical smog in North-American conditions. Furthermore, the use of models that include spatial differentiation in fate and sensitivity are recommended (Udo de Haes *et al.* 1999c). For each of these impact categories, recent research for European conditions has demonstrated the potentially important influence of release location on the magnitude of the expected impact. The US Environmental Protection Agency has developed sets of regionalized characterization factors for the United States employing regionalized fate and transport modeling. The resulting factors differ regionally by more than an order of magnitude and it has been demonstrated that the release location can in some instances be more important than the type of the pollutant for these impact categories (Norris 2003).

Local impacts include eco-toxicity and human toxicity. The unlimited number of species and the numerous environmental mechanisms involved in eco-toxicity impacts cause endpoint modeling to be perceived as being unscientific. Current best available practice is to use indicators for species composition from one or more hypothetical ecosystems (i.e. terrestrial and aquatic) as a whole (e.g. indicators based on the concentration at which 95% of species of a hypothetical ecosystem are regarded as protected based on sensitivity distribution and extrapolation factors). For human toxicity, the main recommendation is to use subcategories for different types of disability (e.g. cancer, fine dust, radiation) (Udo de Haes 1999c).

b. Issues Related to the Inclusion of Optional Elements

- **Normalization**

The objective of normalizing the category indicator results is to understand better their relative magnitude by dividing the potential impact per functional unit by the impact score of a reference situation. The normalization reference is therefore a choice that will strongly influence the normalized profile results.

Examples of normalization references include emissions or use of resources per capita from a defined area, and a baseline scenario for the system under study (ISO 2001). The former is usually used since it is very difficult to find complete inventory data for a scenario with a goal and scope consistent to the system under study.

Most recently published normalization scores are from the Netherlands (1997/1998), Western Europe (1995), and the world (1995), and they present large uncertainties due to the limited set of emissions data, particularly with respect to toxic substances, nitrogen, phosphorus, and hydrocarbons (Huijbregts *et al.* 2003).

- **Weighting**

Weighting is the process of converting indicator results by using numerical factors based on value choices. It can include the aggregation of the weighted indicator results in a few scores or in a single score (ISO 2001a).

The question of weighting arises when trade-offs of different kinds of environmental impacts are involved; that is, when it cannot be unambiguously decided that one option is environmentally preferable to another for all the impact categories included in the study. ISO recommends not using weighting for comparative assertions disclosed to the public (ISO 2001a). Despite this restriction, the use of weighting has gradually increased and it is now regularly used as an in-company-tool (Udo de Haes *et al.*, 2002; Bengtsson, 2000).

Available weighting methods have been classified into one of the following categories: panel method (i.e. weights are defined by a panel of experts and/or users), monetary method (i.e. weights are based on society's willingness to pay to avoid the impacts) and distance-to-target method (i.e. weights are derived from the extent to which actual environmental performance deviates from set targets) (Finnveden 1999). Different weighting methods may lead to different results. However, they remain a controversial issue, and there is no single favoured weighting method for use in LCA (Udo de Haes *et al.* 2002; Hofstetter 1999; Finnveden 1999). Furthermore, the use of the distance-to-target weighting method has been discouraged, unless it is explicitly assumed that all targets are of equal importance (Udo de Haes *et al.* 2002; Finnveden 1999).

Current research studies are oriented towards including multicriteria approaches on weighting procedures (Benoit *et al.* 2003; Seppala 2003; Seppala *et al.* 2002; Seppala *et al.* 2001).

4.1.4 Interpretation

The interpretation step serves to evaluate the study in order to draw conclusions, explain limitations, and give recommendations based on the inventory analysis and impact assessment results. The results of this phase may lead to an adjustment of the goal and scope or to further investigations of the inventory and associated impacts.

Figure 4.5 presents the elements of this phase according to ISO 14043 (ISO 2001b).

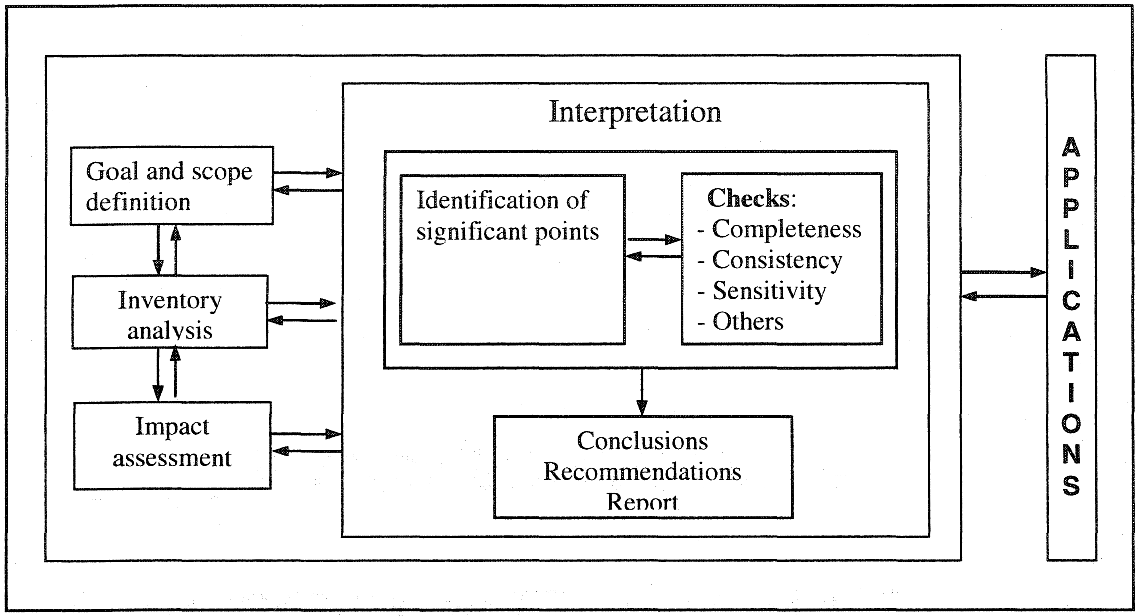

Figure 4.5: Elements of interpretation phase according to ISO 14043

The identification of significant points is performed based on the goal and scope of the study and the intended application. They can include methodological choices (e.g. allocation rules, selection of impact category, category indicators, and models, etc.), inventory data, impact categories, or significant contributions to the LCI and LCIA results. The interpretation checks include completeness (i.e. to assure that all the pertinent information is complete), sensitivity (i.e. to determine whether the results are affected for the uncertainties on the study) and consistency (i.e. to determine if the assumptions, methods and data are coherent with the goal and scope of the study) (ISO 2001b). Completeness and consistency checks are considered as qualitative or procedural steps, while sensitivity checks are viewed as a quantitative or numerical step (Heijungs *et al.* 2001).

Current debate on the interpretation phase is mainly oriented towards the numerical steps and the assessment of different types of uncertainties. There is still a lack of consensus about how these issues should be handled (Bjorklund, 2002) and therefore these analyses are usually excluded from LCA studies. In a recent survey of thirty case studies, it was found that only three of them included some sort of uncertainty assessment (Ross *et al.*, 2002).

a. Types of Uncertainties in LCA and Existent Frameworks for their Assessment

- **Parameter Uncertainty**

This includes the uncertainty on the inventory data and the data used for the calculation of impact assessment factors (i.e. characterization, normalization and weighting). Sources of parameter uncertainties are: lack of data, inaccuracy, and unrepresentativity (Huijbregts 1998a).

LCA practitioners mostly have to deal with parameter uncertainties on inventory data that they collect and model in order to study a system. For such purposes, several frameworks have been proposed (Huijbregts 2001b; Maurice 2000; Huijbregts 1998b; Weidema 1996).

To fill data gaps in life cycle inventories, mass and energy balances or models that calculate direct and indirect emissions and resources, using the estimated price of missing flows as input, are recommended. Missing data can also be estimated by using information for the most similar process or product for which data are available or for the main ingredients of the product. These sources may also be used to further specify sum parameters (e.g. hydrocarbon emissions) (Huijbregts *et al.* 2001b).

The Monte Carlo simulation is usually recommended to assess the inaccuracy and representativity of the inventory data (Huijbregts *et al.* 2001b; Maurice *et al.* 2000; Huijbregts, 1998b). However, in practice, it is very difficult to obtain uncertainty distributions for the large amount of parameters included in the inventory analysis. Therefore, a prior identification of key parameters is proposed by means of a broad sensitivity analysis using standard uncertainty estimates (Sakai *et al.* 2002; Heijungs 2001; Heijungs 1996). However, a disadvantage of using a standard sensitivity range is that parameters with a minor contribution to LCA outcomes, but with a large unknown uncertainty range, are eliminated from the analysis (Huijbregts 1998b). An alternative approach is to identify the key input parameters based on the contribution of input data to the results and a qualitative assessment of the data uncertainty (Maurice *et al.* 2000). Contributions can be calculated from current LCA software and uncertainty can be qualitatively assessed using data quality indicators (i.e. an ordinal scale with numbers ranging from 1 to 5) (Weidema 1998).

After the key input parameters have been identified, a quantitative uncertainty analysis can still remain complicated because of a lack of knowledge about the actual uncertainty of input data. One alternative can be the use of expert judgement to estimate uncertainty ranges (Huijbregts 2001), or the use of proposed guidelines which are based on the amount of data available for the model parameters (Maurice 2000; Finnveden 1998; Hanssen *et al.* 1996).

The assessment of the uncertainty of the characterization factors on LCA study outcomes has been illustrated for the comparison of insulation thickness in buildings (Huijbregts 2001a), but there is no evidence of its inclusion in real studies because the uncertainty of characterization factors is generally unknown. Model developers generally do not provide quantitative information about parameter uncertainty, except for some references about midpoint modeling of toxicity potentials (Hertwich *et al.* 2000; Huijbregts *et al.* 2000; Hertwich *et al.* 1999). Because normalization and weighting are optional steps and the methodological choices involved in their application are supposed to have a stronger effect on the study results, parameter uncertainty of the normalization and weighting factors are not covered in the literature.

- **Uncertainty due to Choices**

Several choices are made when performing LCA studies (e.g. system boundaries, allocation rules, characterization models, weighting factors, etc.). The use of guidelines such as SETAC Best Available Practices (Udo de Haes *et al.* 2002) and ISO standards (ISO 1997; ISO 1999; ISO 2001a; ISO 2001b) as well as peer-review processes are useful practices to reduce uncertainty due to choices (Huijbregts 1998a). Uncertainties due to choices can be quantitatively assessed, as has been illustrated for the comparison of two types of roof gutter, where the combined effect of parameter uncertainty and uncertainty due to choices in inventory data and characterization factors were calculated (Huijbregts 1998b).

- **Model Uncertainty**

There can be model uncertainties in LCA studies due to several factors, including the lack of temporal and spatial variability, linearity in the assessment, and model uncertainties on the simplified environmental models used to calculate characterization factors, etc. At present, model uncertainty assessment has not been made operational in LCA case studies (Huijbregts 1998b).

4.2 Benefits and Limits of LCA Methodology

LCA is the only tool that can be used for product comparisons over the whole life cycle (Finnveden 2000). The main benefits of using this methodology have been highlighted by ISO and SETAC as (Owens 1999):

- Quantifying material and energy efficiency for a system
- Identifying improvement opportunities and trade-offs
- Illuminating hidden or unrecognized issues
- Promoting a wider communication about how to compare and improve highly complex and difficult to analyze industrial systems

However, since LCIA addresses only the environmental issues that are identified in the goal and scope, it is not a complete assessment of all environmental issues. Furthermore, LCIA is fundamentally an analysis of inputs from and outputs to the environment rather than an analysis of the actual environmental consequences or effects from a system. Impact assessment modeling in LCA involves in some cases highly simplified assumptions about complex environmental processes (e.g. eco-toxicity) and there are also difficulties in dealing with spatial, temporal and dose-response issues (Owens 1999).

Therefore, even for comparisons, complementing LCA results with the absolute approaches of other techniques (e.g. risk assessment) has been suggested. The system-wide, relative LCA approach can identify and analyze possible system issues and trade-offs, whereas absolute tools would analyze in detail the issues raised by LCA (Owens 1999). Other limitations of the methodology include the uncertainty of the results due to data gaps, data uncertainties, methodological choices, and values. However, these are relevant also for other environmental tools (Finnveden 2000).

4.3. Application of LCA in the Pulp and Paper Industry

A recent survey (Gaudreault *et al.* 2004) showed that LCA applications in the pulp and paper industry have evolved from traditional product comparison (e.g. paper vs. plastic bags) to process analysis (e.g. emissions assessment along the paper cycle), comparison of technological options (e.g. wastepaper management options), and, to a lesser extent, strategic evaluation (e.g. supply chain structuring). However, there is no evidence that LCA is currently being implemented at the industry level, as most of the reviewed studies were performed by universities. Furthermore, the countries where the case studies were performed are mostly European, and only 2 out of 33 studies were performed in Canada (Gaudreault *et al.* 2004).

Another important finding of this survey was that often the published case studies presented incomplete LCA methodologies. Around half of them were limited to the inventory analysis phase and most of them did not present the interpretation checks in the publications. This latter fact might affect the credibility of the studies. Nonetheless, an improvement in the completeness of the studies has occurred as a consequence of the methodology standardization by ISO (Gaudreault *et al.* 2004).

In Canada, the Pulp and Paper Association developed a voluntary environmental profile program as a response to market demands for detailed environmental information on the environmental burdens associated with the life cycle of products. The objective of the program was to provide environmental product information to customers, including a life cycle inventory of the production phase and specific indicators of upstream processes (sustainable forestry practices, energy use for key bleaching chemicals), two impact categories (global warming and acidification), non-LCA elements such as risk assessment (e.g. effluent toxicity characteristics), and the implementation of environmental management systems (Terrachoice 1997).

4.4. LCA in the Context of Process Design

In the various evolutionary phases of process design, criteria and measures are needed for comparing the environmental benefits of alternatives. LCA offers potential for providing such criteria and measures. Furthermore, the use of LCA in process design allows for incorporating environmental considerations at an early stage of the design, alongside the more traditional and economic criteria. The conventional system boundary is extended to include the life cycles of different processes, all the way from extraction of primary resources through to production. Therefore, LCA offers a potential for technological innovation in the process concept and structure through the selection of the best technologies and raw materials over the whole cycle (Azapagic 1999).

However, LCA only provides information on the environmental releases, burdens or impacts of the system under study. Therefore, it is important that the results of LCAs are interpreted in conjunction with social, economic and technical considerations to enable more balanced decisions. For example, the total economic and environmental burdens of a process can be quantified by performing an LCA in conjunction with a techno-economic feasibility study (Burgess *et al.* 2001).

CHAPTER 5 – SYNTHESIS AND CRITICAL REVIEW

The last three chapters presented key technical issues related to newsprint life cycle, the environmental aspects of its production at integrated mills, and the life cycle assessment methodology.

In Chapter 2, a general newsprint life cycle was described with a special focus on the newsprint production stage. Main production processes were explained in terms of process configuration, resource consumption and waste generation. Various technological options in the Canadian context were presented and their advantages and disadvantages were discussed for most of the processes, especially for the management practices of forest harvesting, process wastes, and wastepaper. Transportation was presented as part of the fibre supply and distribution systems. Finally, the benefits of integrated operations were highlighted since they are significant from both an economical and environmental perspective, by allowing the reuse of mass and energy waste streams.

In Chapter 3, the main sources of water and air discharges from newsprint production at integrated mills were identified and their potential effects on the environment were discussed. Among water discharges, organic and nutrient loads are especially of interest, since some eutrophication effects have been detected due to effluents from Canadian mills. Air emissions from combustion processes and VOCs from thermomechanical pulping are the most important air emissions. These are of concern because of the impact of air quality on human health. In the last decade, Canadian pulp and paper mills have significantly improved their environmental performance by implementing de-inking processes, secondary effluent treatment, and closing their water cycles. These improvements were mostly regulation-driven. However, besides more stringent regulations, there are other motivations for continuous environmental improvement such as international commitments (i.e. Kyoto Protocol, UN Convention on Biological Diversity) and the demand for greener products from exportation markets. Therefore, environmental strategies to further reduce the impacts from newsprint mills are under debate, such as an increase in de-inking, electricity cogeneration, and zero effluent technologies. Their advantages and disadvantages as well as the main constraints for their implementation were presented in Chapter 3. In general, the discussion was based on the techno-economical feasibility, their effects on the process, and on the environment, however without a life-cycle perspective.

Chapter 4 presented an overview of the LCA methodology based on international standards (i.e. ISO and SETAC). LCA is a methodology still under development and there are some areas that are currently debated (i.e. impact assessment modeling, results interpretation). Chapter 4 discussed different approaches for these issues and presented the benefits and limits of the methodology.

Finally, the current status of the LCA application in the pulp and paper industry around the world was analysed based on a recent survey. LCA applications in the pulp and paper industry have evolved from product comparisons to process analysis and technical options comparisons. However, there are some limitations on the reviewed case studies, mostly related to the methodological topics that are still under debate.

The review literature showed the pulp and paper industry as an important industrial sector in the Canadian context with many incentives for continuously improving its environmental performance. Newsprint mills can benefit from the use of LCA methodology by the identification of improvement opportunities in their operations with advantages not only to the receiving environment, but also to the whole product life cycle. The potential advantages include the quantification of consequent benefits and impacts, as well as a clearer communication of these facts to the stakeholders. LCA results can also be taken as input indicators for the overall decision-making process when evaluating different process modifications or environmental strategies.

However, LCA is an emerging technology with a methodological framework still under development. Areas such as methodological choices as well as results interpretation need a deeper analysis based on the intended application of each LCA study. The approaches to be proposed must be practical, but also well justified in order to ensure their reliability and their ease of implementation at the industrial level.

Specifically, the following issues have been identified as important for the application of LCA in the pulp and paper industry, but not well addressed in the literature:

- The need of systematically-executed and well-documented LCA studies in order to demonstrate the value of LCA to industry sectors.
- The potential benefits of using LCA to address important practical applications, i.e. to resolve critical industry issues by comparing process variants.
- The potential opportunity to address the broad environmental questions surrounding current environmental strategies in the pulp and paper industry, and in particular for integrated newsprint mills, such as:
  - The conditions under which environmental benefits are clear, related to the implementation of DIP/cogeneration
  - The environmental benefits due to the implementation of additional effluent treatment or process closure
  - The most environmentally-friendly manner for managing wastepaper including curbside collection and transportation issues.

PART II – EXPERIMENTAL

CHAPTER 1 – PROBLEM INTRODUCTION AND CONTEXT

LCA applications in the pulp and paper industry have evolved from product comparisons to process analysis and technical options comparisons. However, there is no evidence that the case studies include all the ISO 14040 elements, especially those related to the interpretation of results (Gaudreault et al. 2004). This can be explained by the fact that the ISO standard on this last LCA stage is relatively recent and presents a general framework with little practical guidance.

The objective of the interpretation phase has been stated by ISO as follows: "to evaluate the study in order to draw conclusions, explain limitations and give recommendations based on the inventory analysis and impact assessment results" (ISO 2001). However, the type of conclusions sought from the study will depend on the intended application and thus affect the approach used for interpreting the results. For instance, for process analysis applications (i.e., attributional, retrospective, descriptive, or accounting LCA studies), the conclusions are generally oriented towards the "hot spots" or the main opportunities to improve the environmental performance. When alternative options are compared (i.e., consequential, prospective, comparative, or change-oriented LCA studies), the conclusions are focused on the identification of the option that is most environmentally sound.

This research is focused on the interpretation of results for process analysis studies. Various numerical steps have been proposed so far to address this issue, including contribution, perturbation, and uncertainty analyses (Heijungs et al. 2001). In practice, the problem in the identification of improvement opportunities arrives when various impact categories are assessed and the contribution from different processes varies across them. A review of published case studies shows that they usually deal with this issue by analyzing the contribution on a weighted profile of impact categories; however, this profile is generally calculated using commercial weighting factors, which in many cases do not correspond to the study context and add subjectivity to the analysis. Furthermore, the sensitivity of the results on the weighting factors is typically not addressed (see, e.g., INFRAS 1998). There is still the option of identifying the improvement opportunities per impact category, and in fact this is the second most common approach used in practice; but again, a complementary uncertainty assessment is generally lacking (Dias et al. 2002).

The common exclusion of uncertainty assessments from LCA case studies has also been explained by the lack of consensus about how these issues should be handled. The proposed methodologies have evolved from qualitative methods to quantitative tools, to frameworks that integrate quantitative and qualitative approaches (Bjorklund 2002). Among these latter, the Monte Carlo simulation is generally recommended to assess parameter uncertainty and uncertainty due to choices (see, e.g.,, Huijbregts 2001); however, in practice, it is difficult and time demanding to obtain the probability distributions necessary for this kind of assessment, and their estimations introduce additional uncertainty to the analysis.

In this research study, we propose an alternative interpretation approach for the integrated analysis of the improvement opportunities for environmental performance as well for data quality, through the comparative evaluation of the sensitivity of results key model parameters. This new approach is based on an easy-to-perform and reliable sensitivity analysis technique, and does not have to deal with the subjectivity of the valuation steps, or with the constraints of using more sophisticated and time-demanding uncertainty assessments.

In order to illustrate this new approach, an LCA baseline model was developed. The system studied is the production of standard newsprint with 20% recycled pulp content, from the raw material extraction to the newsprint distribution (i.e., cradle-to-gate). The main production chain includes woodlands, a sawmill and a newsprint mill. These operations are managed by the same company and are located in Northern Ontario. Finally, the baseline model is also used to show the potential benefits of alternative mill configurations, which are designed on the basis of the identified improvement opportunities and the current environmental strategies in the pulp and paper industry.

CHAPTER 2 – SUMMARY OF THE LITERATURE REVIEW

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts associated with a product or process during its entire lifetime. Its potential applications include the identification of improvement opportunities, as well as use as a decision-making tool in strategic planning and product or process design (ISO 1997). LCA consists of four phases: the first phase, goal and scope definition, serves to define the purpose and the extent of the study, and it contains a description of the system studied; the second phase, the inventory analysis (LCI), involves the collection and analysis of data on mass and energy inputs and outputs of the processes included in the system boundaries; the third phase, impact assessment (LCIA), is the evaluation of the significance of the environmental stressors contained in the LCI, and its purpose is to determine the relative importance of each inventory item and to aggregate the stressors to a small set of indicators (i.e., impact categories); the last phase, interpretation, is the evaluation of the study in order to derive recommendations and conclusions.

LCA methodology is presently undergoing a harmonization process performed by the International Standardization Organisation (ISO), the United Nations Environmental Program (UNEP), and the Society of Environmental Toxicology and Chemistry (SETAC). Topics that are still under discussion include impact assessment modeling and the interpretation of results phase.

The pulp and paper industry is an important industrial sector in the Canadian context with many motivations for continuously improving its environmental performance. Besides more stringent regulations, there are international commitments (i.e., Kyoto Protocol, UN Convention on Biological Diversity) and the demand for greener products from exportation markets. In this sector, the application of LCA for process analysis and for comparing improvement options has increased in recent years, but the interpretation of the study results is usually not clearly covered or is missing from most of the published case studies (Gaudreault *et al.* 2004).

ISO proposes a general procedure consistent with the identification of significant points and the performance of interpretation checks. They recommend identifying the significant points based on the goal and scope of the study and the intended application; these can include methodological choices, inventory data, impact categories, or significant contributions to the LCI and LCIA results. The proposed interpretation checks include completeness (i.e., to assure that all the pertinent information is complete), sensitivity (i.e., to determine whether the results are affected for the uncertainties on the study) and consistency (i.e., to determine if the assumptions, methods, and data are coherent with the goal and scope of the study). Furthermore, ISO recommends complementing these checks with uncertainty and data quality assessments (ISO 2001).

There is still a lack of consensus about how to handle this last ISO recommendation and, consequently, it has typically been excluded from LCA studies. The Monte Carlo simulation is usually recommended to assess parameter uncertainties in LCA (Huijbregts 2001; Maurice et al. 2000). However, in practice, it is very difficult to obtain uncertainty distributions for the large amount of parameters included in the inventory analysis. Therefore, a prior identification of key parameters is proposed by means of a broad sensitivity analysis using standard uncertainty estimates (Sakai et al. 2002; Heijungs et al. 2001). A disadvantage of this approach is that parameters with a minor contribution to LCA outcomes, but with a large unknown uncertainty range, are eliminated beforehand from the analysis (Huijbregts 2001). An alternative approach is to identify the key input parameters based on the contribution of input data to the results and a qualitative assessment of the data uncertainty (Maurice et al. 2000).

After the key input parameters have been identified, a quantitative uncertainty analysis can still remain complicated because of a lack of knowledge about the actual uncertainty of input data. One alternative can be the use of expert judgement to estimate uncertainty ranges (Huijbregts 2001), or the use of proposed guidelines that are based on the amount of data available for the model parameters (Maurice et al. 2000).

There is uncertainty associated not only with the inventory data, but also with the characterization factors used for the impact assessment. The uncertainty assessment of the latter has been illustrated for the comparison of insulation thickness in buildings (Huijbregts 2001), but its inclusion in case studies remains even more complicated because the developers of impact assessment models generally do not provide quantitative information about the uncertainty of their characterization factors, except for some references about midpoint modeling of toxicity potentials (Hertwich et al. 2000).

Apart from the parameter uncertainty, several choices are made when performing LCA studies that can add uncertainty to the results (e.g., system boundaries, characterization models, weighting factors, etc.). The use of ISO standards and the performance of peer-review processes are useful practices to reduce uncertainty due to choices. Uncertainties due to choices can be quantitatively assessed, as has been illustrated for the comparison of two types of roof gutter, where the combined effect of parameter uncertainty and uncertainty due to choices in inventory data and characterization factors were calculated (Huijbregts 2001).

Finally, there can be model uncertainties in LCA studies due to several factors, including the lack of temporal and spatial variability, linearity in the assessment, and model uncertainties on the simplified environmental models used to calculate characterization factors, etc. At present, model uncertainty assessment has not been made operational in LCA case studies (Huijbregts 2001).

CHAPTER 3 – CASE STUDY BACKGROUND

Spruce Falls Inc. (SFI) is an integrated mill located in Northern Ontario, whose main product is standard newsprint. The virgin fiber required for the process is obtained from the woodlands and sawmill owned by the same company, Tembec. These three business units, the woodlands, sawmill and newsprint mill, have environmental management systems certified under ISO 14001. Furthermore, SFI annually informs the general public about the environmental burdens associated with the life cycle of its products, as part of the voluntary profile program from the Canadian Pulp and Paper Association (i.e., EPDS). Following good environmental practices, SFI was interested in the development of a baseline model for newsprint production that can be integrated with its environmental management system in the future.

Furthermore, as part of its environmental policy, SFI aims for continuous environmental improvement. This aspiration is driven by the stakeholders' concerns, such as more stringent regulations, international commitments, and the demand for greener products from their international clients. In this context, the assessment of environmental strategies to be implemented in the future can be enhanced by the inclusion of the life cycle perspective in the analysis.

The process of newsprint production at SFI is depicted in Figure 3.1. At the woodlands, spruce (softwood) and aspen (hardwood) are produced. The raw material used for newsprint production is spruce, which represents 75% by volume of the total woodland production. Aspen is used for plywood production. During winter, softwood logs are transported by truck to the sawmill located on site at the integrated newsprint mill. Sawmill operations convert the logs to lumber as the main product, and chips are generated as a co-product, while bark and shavings (i.e., hog fuel) are produced as wood wastes. Lumber is a finished product sold to the construction industry. Chips are used to produce wood pulp in a thermo-mechanical pulping (TMP) process, while hog fuel is burned at the boiler house in order to produce the steam necessary for the newsprint production process. The on-site sawmill provides around half of the chips and hogfuel necessary for the newsprint production process, and the remainder is supplied by local sawmills.

Virgin pulp is obtained from the TMP process, which has a high yield and is very energy intensive. The refining stage consumes the highest amount of electricity in the newsprint mill, but part of this energy is recovered as steam. Due to the high temperature of chip refining, some of the volatile wood compounds are evaporated during this process. These VOC emissions are partially recovered in the heat recovery unit and the rest are emitted to the atmosphere.

Recycled pulp is obtained from old newspapers and old magazines by a de-inking pulping (DIP) process. Wastepaper furnished to DIP processes is purchased mainly from Ontario or the USA, and transported to the newsprint mill by truck or rail. The yield of this process is lower than for TMP due to wastepaper contaminants such as dirt, tramp metal, adhesives, coatings, and ink. However, part of the generated solid wastes (i.e., sludges) can be burned in the boiler house to produce steam.

Pulp produced in the TMP and DIP processes is then furnished to four paper machines where water is eliminated from the pulp, and newsprint is obtained. A significant amount of steam is required for this process and most of the water eliminated from the pulp is recycled to the process. These paper machines also produce a specialty paper product derived from TMP pulp called Uncoated Groundwood Specialty (UCGS), but in much smaller quantities, around 15% of the total yearly tonnage.

The steam required at the mill is produced from natural gas and biomass (i.e., hog fuel and sludges from DIP and effluent treatment processes) combustion in the boiler house.

The main emissions from the boiler house include combustion gases and particulates, as well as ashes, which are landfilled on site.

The effluents from the processes described above receive both primary (i.e., gravity separation) and secondary (i.e., biological) treatment before being released to the river. The main emissions after treatment include BOD (biochemical oxygen demand), TSS (total suspended solids), and nutrients (i.e., nitrogen and phosphorus). The sludges produced in the effluent treatment plant are mixed with those from the DIP process and then dewatered. Finally, a portion of the solid waste is burned in the boiler house and the rest is landfilled on-site.

Most of the electricity consumed in the newsprint production process is purchased from the grid and its average source breakdown is: 33% fossil (coal), 39% nuclear, and 28% hydroelectric. The main fuels used in the process are natural gas for steam production and diesel for transportation. The chemicals most frequently employed in the pulping process include sulphur dioxide, soda, sodium silicate, borol, and hydrogen peroxide. Finally, the produced newsprint is distributed to newspaper printing facilities in Ontario, Quebec, and US cities by truck or rail.

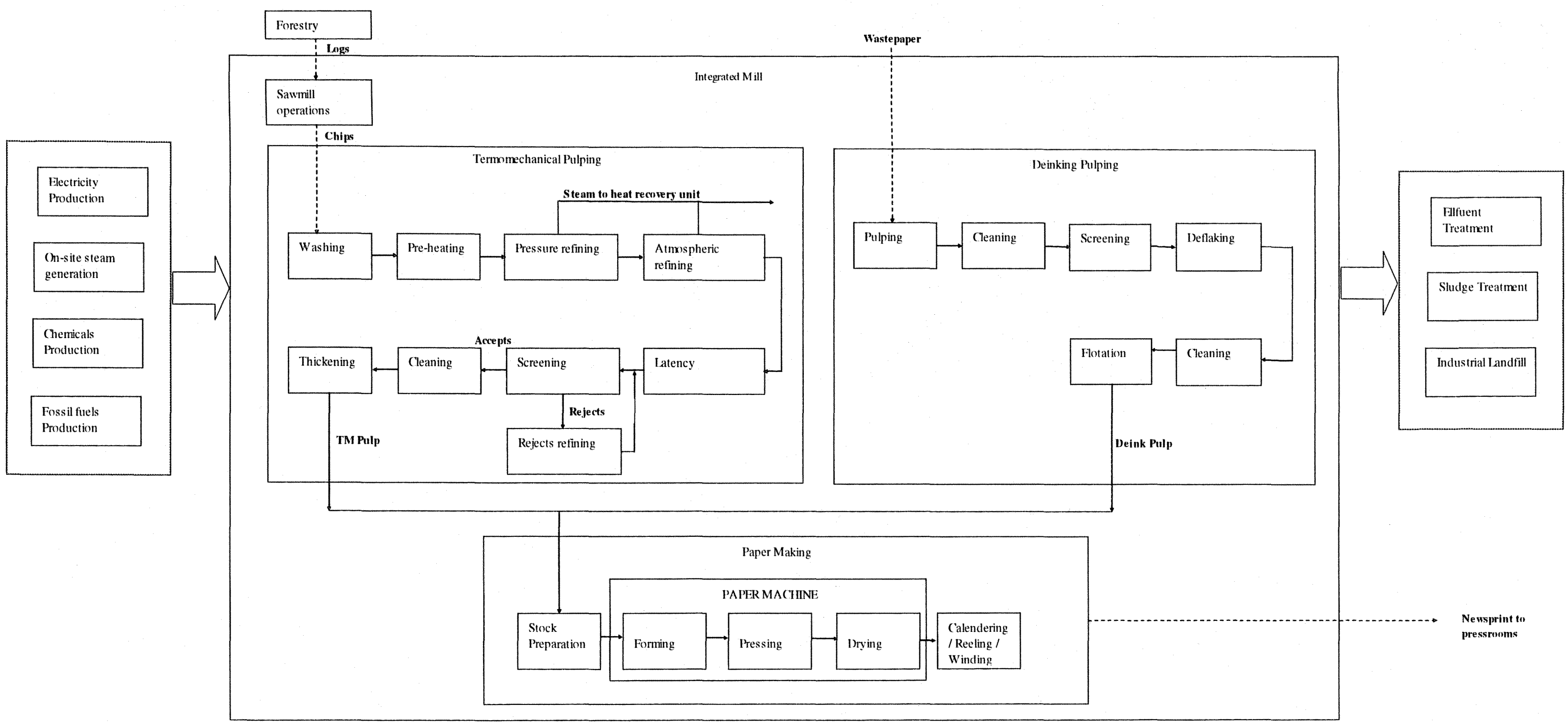

Figure 3.1: Newsprint production system

CHAPTER 4 – OBJECTIVES AND HYPOTHESES

The overall objectives of this research project are to:

- develop an LCA baseline model for newsprint production suitable for the assessment of process variants
- propose a systematic procedure for the interpretation of the baseline model results oriented towards the identification of newsprint mill opportunities to improve the life cycle environmental performance
- show the potential benefits of the identified improvement opportunities by the assessment of alternative newsprint mill configurations

The research hypothesis is proposed as follows:

The results of an LCA baseline model can be systematically used and in a practical manner, in order to identify process opportunities to improve life cycle environmental performance using sensitivity analysis, thereby separating valuation elements in the assessment.

The following sub-hypotheses are related to the case study that is used for the demonstration of the main hypothesis:

- The increase of DIP production and the implementation of co-generation systems involve potential benefits for the whole production chain. These benefits strongly depend on the primary source of electricity.
- The life cycle environmental performance of newsprint production can be improved by the implementation of additional water treatment (i.e., tertiary

treatment) or process closure (i.e., zero effluent) at the integrated newsprint mills.

- LCA can be used to address the debate over the most environmentally-friendly manner for managing wastepaper including curbside collection and transportation issues.

CHAPTER 5 – METHODOLOGY

The methodology applied for this study is depicted in Figure 5.1. The steps are grouped into the four phases of the LCA methodology which are briefly explained below. Details on the methodology are presented in the following appendices:

- Appendix A: Presents details on the methodology employed for the baseline model development and the interpretation of its results.
- Appendix C: Presents details on the system modeling, specifically related to the inventory analysis of each unit process included in the system boundaries.
- Appendix D: Presents an analysis of the inventoried substances not characterized by the selected impact assessment methods.
- Appendix E: Presents details on the definition of uncertainty ranges for the selected key parameters during the interpretation phase.
- Appendix F: Presents the report of the peer review performed on the employed methodology.

5.1 Goal and Scope Definition

Various elements, including the main methodological choices, were defined at the beginning of the study as part of this phase. The most important are the following:

- *Goal of the study*: The goal of this study is to identify process opportunities to improve the life cycle environmental performance. The developed baseline model is also intended to be used in future studies for the assessment of process variants.
- *Functional unit*: The production of 1 admt (i.e., 1 air dried metric ton, 10% moisture content) of newsprint.

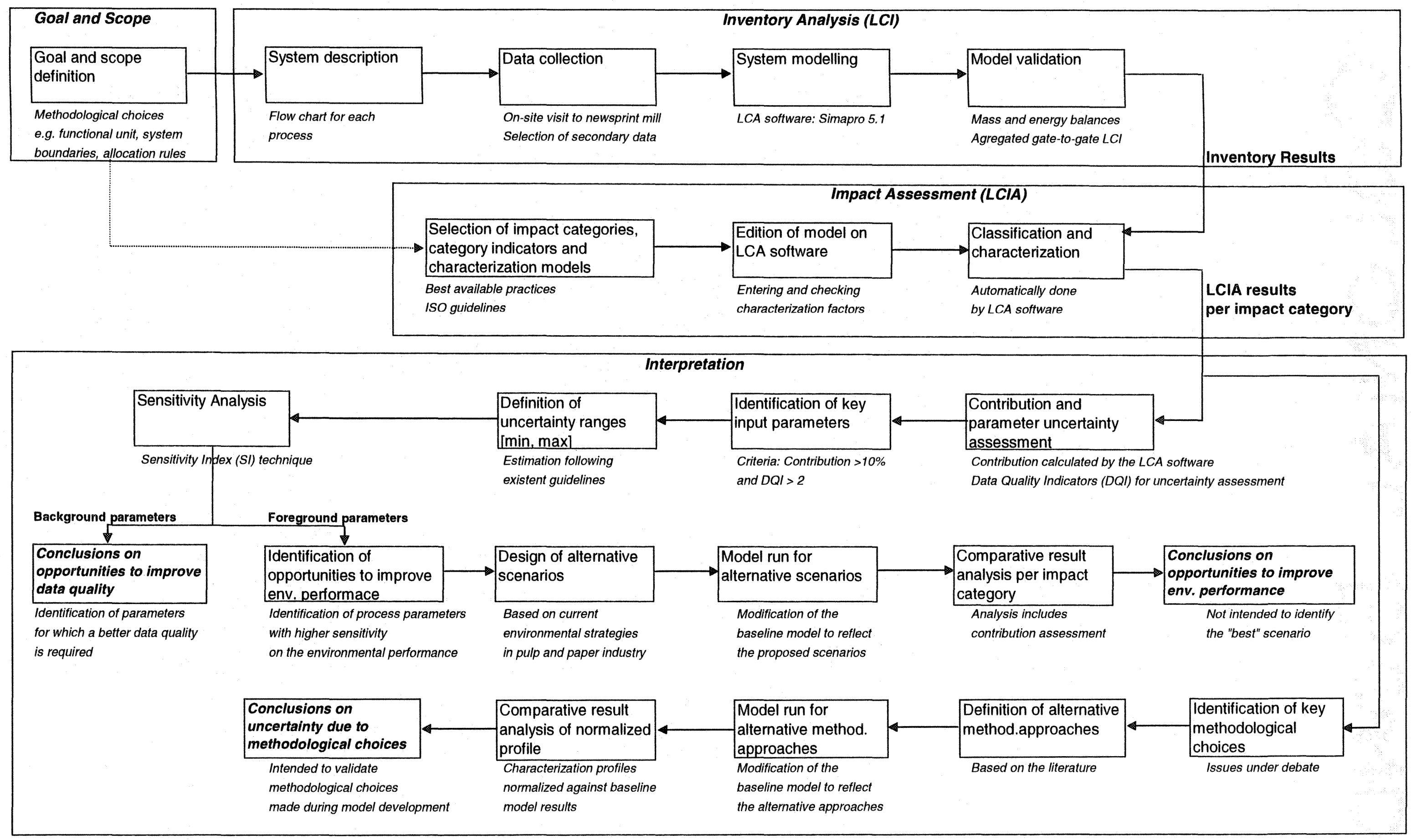

Figure 5.1: Methodology for the life cycle assessment of newsprint production

- *System boundaries*: Includes unit processes from wood extraction at woodlands to newsprint distribution (i.e., from cradle-to-gate). In this case, an exception is made referred to the ISO recommendation of defining the system boundaries from cradle-to-grave, based on previous related studies where it was found that the impacts related to the use and end of life are negligible in comparison to those from the production and up-stream unit processes (INFRAS 1998, Dias et al. 2002). The defined system boundaries are presented in Figure 5.2.

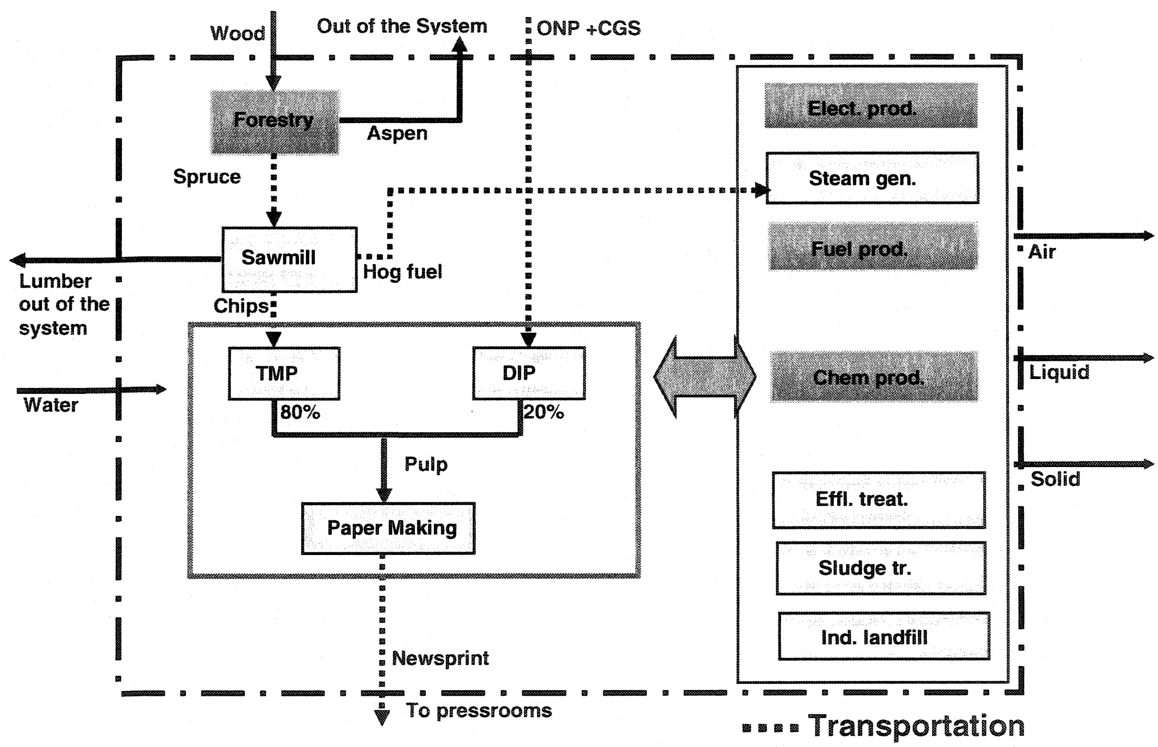

Figure 5.2: Defined system boundaries for the system studied

- *Allocation rules*: By products are produced in woodlands, sawmill and paper mill. In these cases, the defined allocation rules are based on: volume for woodlands; and on mass for sawmill and paper machines, following recommendations by Jungmeier et al. (2002b). Environmental burdens allocated to aspen, lumber, and UCGS were excluded from the system since they are not used for newsprint production.

5.2 Inventory Analysis

During this phase, a special focus was placed on system understanding and modeling since LCA is a broad engineering tool where hundred of inventory parameters are finally manifested in a few indicators. Therefore, as an initial step, flow charts for each of the processes at the integrated mill were developed, including the main mass and energy inputs and outputs, based on a literature review and previous simulation studies. After identifying the process parameters, data sources were selected and a first cut of the inventory model was developed in Simapro 5.1, using available primary and secondary information for each unit process. This first cut was then refined after visiting the integrated mill and gaining a better understanding of the real process. Then, the model was validated using mass and energy balances and the Environmental Profile Data Sheet (EPDS), an aggregated life cycle inventory that the newsprint mill manages for information purposes. Finally, the inventory results per 1 admt of newsprint were automatically generated by the LCA software.

The consumption of energy, water, and fuels for administrative activities, as well as the generation of office wastes, are included in the inventory despite the fact that these parameters do not have a linear relationship with the functional unit. For instance, the production of 2 admt of newsprint does not imply an increase of 100% in the energy required for office heating. On the other hand, the contribution from these activities is negligible and they were included for completeness purposes and to be consistent with the EPDS approach. The future applications of the baseline model for comparative purposes should evaluate the convenience of excluding these activities from the inventory analysis.

5.3 Impact Assessment

There are several available models for the assessment of environmental impacts in life cycle studies (e.g., eco-indicator, EDIP, CML, TRACI, etc.), and thus the task in this phase is to select the impact categories and the characterization methods according to the context and the goals of the study. This important methodological choice was made following ISO 14042 guidelines and SETAC best available practices.

In summary, only the output related impact categories (i.e., caused by the emissions from the system to the environment) were selected since the input related ones (i.e., caused by the resource consumption of the system from the environment) are still under development. Among the output-related categories, the characterization model selection for global impacts (i.e., global warming and ozone depletion) was straightforward since there is an international consensus in this regard. However, for the regional and local impacts, there is debate concerning the spatial differentiation that has been shown to significantly affect the characterization results. Therefore, a recent method developed by the USEPA, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), which includes spatial differentiation among US states for the modeling, was selected and its compatibility with ISO guidelines and SETAC best available practices was analyzed before its inclusion in the baseline model.

After entering the selected impact assessment method in the LCA software, an edition process was performed in order to include the characterization factors for the state of reference (i.e., Michigan) and to assure the equivalence in nomenclature of the inventory substances in the list of characterization factors. Finally, the classification and characterization steps were performed with the aid of the LCA software, which generated the results per impact category. Optional elements (i.e., normalization and weighting) were not performed, mainly because the related methodology is not well defined at this time.

5.4 Interpretation of Results

This is the LCA phase least defined by the ISO guidelines. Up until now, some frameworks have been proposed, but there is no evidence that the practitioners perform systematic interpretation processes in their case studies, including uncertainty and data quality assessments, as recommended by ISO. The activities performed in this phase constitute the most important methodological contribution of this research project.

In summary, two types of uncertainty were assessed: parameter uncertainty and uncertainty due to choices. The parameter uncertainty assessment was performed with the main objective of identifying process opportunities to improve the life cycle environmental performance, taking into account parameter uncertainties. On the other hand, the effects on the characterization results of using alternative approaches for two methodological choices (i.e., by-product allocation in sawmill operations and system boundaries) were assessed.

The procedure for the parameter evaluation begins with an identification of key parameters. Due to the large amount of parameters included in the inventory analysis, this selection is carried out based on their contribution to the category indicator results and the data uncertainty. Contribution is calculated with the LCA software and the data uncertainty is evaluated using Data Quality Indicators (DQI). Then, uncertainty ranges are defined for the selected key parameters, and the sensitivity on the category indicator results is evaluated using a sensitivity index, defined as the ratio of change in the category indicator results due to the change in one input parameter between its minimum and maximum values (i.e., uncertainty range), while the others are held fixed.

A comparison of the sensitivity indexes among the foreground parameters (i.e., those over which the company has direct control) allows for the identification of mill opportunities to improve the life cycle performance; while the comparison of sensitivity results for background parameters (i.e., those over which the company has no direct control) allows for the identification of parameters for which a better data quality is required.

The foreground parameters are further analyzed through scenario analyses. Alternative scenarios oriented towards the reduction of the impacts from energy consumption and mill effluents are developed and analyzed. Current environmental strategies in the pulp and paper industry are modeled with the aim of increasing DIP production, on-site electricity co-generation, tertiary treatment of mill effluents, and zero effluent technologies. The baseline model was then modified to evaluate the developed scenarios and the results were comparatively analyzed against those from the baseline model. It is important to note that the main objective of these steps was not to identify the "best" scenario, but to illustrate the use of the baseline model in the assessment of opportunities to improve the environmental performance and to show the trade offs of the studied alternatives. Further research that will use this baseline model, such as the projects related to the assessment of major process modifications, and the design of a minimum impact mill configuration, should include modeling techniques specific for comparative LCA studies. These might include improved design criteria, marginal technology approach, refined system boundaries, and complementary interpretation checks for the assumptions made during the scenario development, etc.

In the assessment of methodological choices, two were identified as key, because they are debated issues, namely, the by-product allocation approach in the sawmill operations and the inclusion of the wastepaper collection in the system. The baseline model was modified in order to include the existent alternative approaches and the consequent results were comparatively assessed against those from the baseline model.

5.5 Peer Review

A formal internal peer review of this study was carried out by a committee of three LCA experts from the Interuniversity Reference Centre for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services (CIRAIG) from the Ecole Polytechnique de Montreal, following ISO protocols. The main objective for the submission of this project to the peer review process was to identify the weaknesses of this study and apply corrective actions before its utilization on future research projects related to the intended application. A secondary objective was to ensure the trust from the intended audience in the results and conclusions drawn from the study. The peer review included basically the methodological elements for each of the four LCA phases, and a sample of the calculations performed (around 10%).

CHAPTER 6 – RESULTS AND DISCUSSION

This section presents complementary results of the study. Detailed results and discussion are presented in Appendix B. Additionally, Appendix G presents the inventory results for all the resources and emissions of the system studied and Appendix H presents the unit process contributions to the impact category results.

6.1 Impact Assessment Results

Table 6.1 shows the impact assessment results for the selected impact categories.

Table 6.1: Category indicator results

Impact Categories	Category Indicators	Total
Climate change	g CO_{2eq}	1.20e+6
Ozone depletion	g $CFC11_{eq}$	6.07e-3
Acidification	mol $H+_{eq}$	3.05e+2
Eutrophication	g N_{eq}	4.36e+2
Photo-oxidant formation	g NO_{xeq}/m	2.64e00
Eco-toxicity	g $2,4D_{eq}$	3.20e+3
Human health-cancer	g C_6H_{6eq}	7.61e+1
Human health-non cancer	g C_7H_{7eq}	3.76e+5
Human health criteria pollutants	DALY	1.20e-4

6.2 Interpretation of Results

6.2.1 Contribution Analysis

Table 6.2 presents the percentages of process contributions on the category indicator results. In order to summarize the results, some of the unit processes have been aggregated (i.e., transportation activities, chemical production, and fuel production). Note that a distinction is made in the contribution from the boiler house according to the type of fuel (i.e., biomass combustion and natural gas combustion) because they contribute differently to the impact categories. For instance, CO_2 emissions are considered zero for biomass but not for natural gas. On the other hand, the emissions from the newsprint mill effluent and the industrial landfill represent the contribution from all the unit process included in the integrated mill (i.e., sawmill, TMP, DIP, paper making, boiler house), since all the mill wastes are treated in the same facility. Note also that some results might not add 100% due to rounding errors of the LCA software.

A distinction is made between the unit processes from the foreground system (i.e., caused by direct emissions) and those from the background system (i.e., caused by indirect emissions). It can be observed that for most of the impact categories, except eutrophication, the background system has a higher contribution than the foreground one, especially for ozone depletion, eco-toxicity, human health cancer, and human health non cancer, where the foreground contribution represents less than 5%. Analyzing the background system, the most significant unit process is the electricity production, which contributes to more than 50% of the global warming, acidification, eco-toxicity, and human health (including the three sub-categories) indicators. The contribution of chemical production is rather small for most of the impact categories (<10%), except for ozone depletion (~97%).

6.2.2 Sensitivity Analyses

a. Sensitivity on Foreground Parameters

Table 6.3 presents the sensitivity analysis results for the selected foreground parameters. Data on foreground parameters have low uncertainty since they are mostly measured at the production site. Therefore, the sensitivity of the category indicators depends basically on their contribution: the higher the contribution, the higher the sensitivity. Note that electricity and natural gas consumption have high sensitivity in most of the impact categories and that eutrophication is mostly sensitive to N-t emissions in the newsprint mill effluent. Therefore, the assessment of the process opportunities to improve its life cycle environmental performance is focused on these parameters.

Table 6.2: Contribution (%) of unit processes to the category indicator results

Unit processes	Global warming	Ozone depletion	Eutrophi-cation	Acidifi-cation	Smog formation	Eco-toxicity	Human health cancer	Human health non cancer	Human health criteria pollutants
Foreground system (or contributions from direct emissions)									
Termomechanical pulping (TMP)	0,0	0,0	0,0	0,0	2,1	0,0	0,0	0,0	0,0
Biomass combustion	0,4	0,0	4,5	5,5	18,3	0,0	0,0	0,0	6,9
Natural gas combustion	10,5	0,0	1,7	2,0	6,9	0,0	0,0	0,0	1,4
Newsprint mill effluent	0,0	0,0	77,5	0,0	0,0	0,6	0,0	2,4	0,0
Industrial landfill	7,9	0,0	0,0	0,0	0,4	0,0	0,0	0,0	0,0
Transportation	5,3	0,0	2,4	2,9	12,7	0,0	0,1	0,9	15,4
Background system (or contributions from indirect emissions)									
Electricity production	70,9	0,0	11,1	55,0	32,4	94,7	87,7	74,0	52,7
Chemical production	2,1	96,9	1,2	3,9	4,1	3,3	10,0	6,2	2,6
Fuel production	2,9	3,0	1,6	30,6	23,1	1,4	2,2	16,5	20,9

Table 6.3: Results of the sensitivity analysis (%SI) on foreground parameters

Input parameter	GW	OD	EP	AC	SF	ET	HH-C	HH-NC	HH-CP
Electricity consumption	17,6		3,0	13,9	8,9	21,5	20,3	17,6	13,1
Natural gas consumption	11,8			27,1	23,2			14,3	18,9
Biomass consumption			2,0	2,6	8,0				
EDTA consumption		6,4							
H_2O_2 consumption						0,3		0,3	
NaOH consumption							2,8		
Solid wastes to Landfill	7,3								
Diesel consumption									12,3
N-t emission in the effluent			21,6						

Note: GW: Global Warming; OD: Ozone Depletion; EP: Eutrophication; AC: Acidification; SF: Smog Formation; ET: Eco-toxicity; HH-C: Human Health Cancer; HH-NC: Human Health Non Cancer; HH-CP: Human Health Criteria Pollutant.

b. Sensitivity on Background Parameters

Table 6.4 presents the sensitivity analysis results for the selected background parameters. Data on background parameters have more uncertainty since they are mostly obtained from literature references and commercial databases. As a consequence, we can observe that their sensitivity results are, in general, higher than those for the foreground parameters. Note that the parameters for which large uncertainty intervals were used (due to a lack of more specific information), present higher sensitivity on the category indicators. Therefore, the measures to improve the data quality of these parameters should consider first refining the uncertainty ranges and then, if necessary, the inventory data.

Table 6.4: Results of the sensitivity analysis (%SI) on background parameters

Input parameter	GW	OD	EP	AC	SF	ET	HH-C	HH-NC	HH-CP
NO_X from biomass combustion			5,0	5,8	17,7				
NO_X from gas combustion					7,4				
NOx from electricity production			3,0						
CO_2 from gas combustion	0,0								
CH_4 from industrial landfill	44,2								
CO_2 from electricity production	25,0								
SO_2 from electricity production				15,7					11,0
NO_X from electricity production					12,3				
Hg from electricity production						63,2		48,2	
As to air from electricity production							57,5		
SO_2 from natural gas production				11,1					6,6
VOC from natural gas production					8,7				
Cd to water from natural gas prod.								20,1	
Hg from elect. to produce chemicals						1,6		1,1	
Halon-1301 from EDTA production		73,1							
CFC-114 from EDTA production		34,4							
As to water from NaOH production							75,4		
PM2.5 from road transportation									0,9

6.2.3 Scenario Analyses

a. Energy-Scenarios

Table 6.5 presents the inventory results per 1 admt of newsprint for some important parameters in the scenario analysis. Observe that for all the scenarios the purchased electricity decreases, but the required steam from the boiler house increases to replace the steam recovered in the baseline model from TMP, when 100% DIP is considered, and to generate electricity, when electricity co-generation is considered. As a consequence, there is an increase in natural gas consumption, since the additional steam cannot be produced entirely from biomass because of availability constraints. We can also observe that despite the fact that all the sludge is burned to produce steam, avoiding landfill, there is an increase in the amount of solid wastes to landfill when 100% DIP is considered. This is because the de-inking process rejects secondary fiber contaminants that do not have an alternative management to landfill. Finally, the diesel required for transportation increases due to more hog fuel transportation, when electricity co-generation is considered, and due to more wastepaper transportation, when 100% DIP is considered.

Table 6.5: Inventory results for alternative energy-oriented scenarios

Parameter	Units	Baseline	100% CE	100% DIP	100% CE + 100% DIP
Purchased electricity	GJ	9,3	0,0	3,8	0,0
Co-generated electricity	GJ	0,2	13,9	0,1	5,7
Steam from boiler house	GJ	6,3	22,6	8,6	15,3
Natural gas to boiler house	m^3	65,0	355,0	93,0	179,0
Hog fuel to boiler house	bdmt	0,2	0,5	0,2	0,5
Sludges to boiler house	bdmt	0,1	0,1	0,2	0,2
Sludges to ind. landfill	kg	35,7	0,0	0,0	0,0
Solid wastes to ind. landfill	kg	73,8	63,8	75,1	98,3
Diesel for transportation	L	9,0	10,8	10,6	12,1

Table 6.6 presents the characterization results for the alternative scenarios, while Table 6.7 displays the profiles normalized against the baseline model results. It should be noted that values lower than 1 represent a decrease in the potential impact and, therefore, an increase in the environmental performance. In general, impact categories with high sensitivity with respect to electricity consumption present values lower than 1. Those with high sensitivity to natural gas consumption present values higher than 1, since for all the alternative scenarios, the amount of natural gas consumed increases. The ozone depletion potential presents values higher than 1 when 100% DIP is considered, due to the increased amount of chemicals; and the eutrophication potential remains almost constant.

Table 6.6: Impact assessment results for alternative energy-oriented scenarios

Impact category	Unit	Baseline	100% CE	100% DIP	100% CE + 100% DIP
Acidification	g H+	3,0E+02	5,7E+02	2,6E+02	3,3E+02
Eco-toxicity	m^3/g	3,2E+03	2,9E+02	1,5E+03	3,5E+02
Eutrophication	g N	4,4E+02	4,8E+02	4,4E+02	4,4E+02
Global warming	g CO_2	1,2E+06	1,0E+06	7,9E+05	6,8E+05
Human health cancer	m^3/g	7,6E+01	1,4E+01	4,4E+01	1,8E+01
Human health criteria pollutants	DALY	1,2E-04	1,6E-04	1,0E-04	1,0E-04
Human health non cancer	m^3/g	3,8E+05	3,5E+05	2,6E+05	2,2E+05
Ozone depletion	g CFC11	6,1E-03	6,7E-03	1,1E-02	1,1E-02
Smog formation	g NO_x/m	2,6E+00	5,1E+00	2,7E+00	3,6E+00

Table 6.7: Normalized profile for alternative energy-oriented scenarios (Normalization reference: baseline model)

Impact category	100% CE	100% DIP	100% CE + 100% DIP
Acidification	1,9	0,9	1,1
Eco-toxicity	0,1	0,5	0,1
Eutrophication	1,1	1,0	1,0
Global warming	0,8	0,7	0,6
Human health cancer	0,2	0,6	0,2
Human health criteria pollutants	1,3	0,8	0,9
Human health non cancer	0,9	0,7	0,6
Ozone depletion	1,1	1,8	1,9
Smog formation	2,0	1,1	1,4

Since electricity production represents a significant contribution to most of the impact categories, we analyzed the effect of changing the electricity production model using the power mix of three different Canadian provinces. The corresponding power mixes and the calculated global warming potential per 1 MWh are presented in Table 6.8. The characterization results per 1 admt of newsprint using these three different electricity models are displayed in Table 6.9. We observe that the power mix, which depends on the mill location, dramatically affects the baseline model results. Therefore, the results presented in this study are valid only for the system studied and no generalization can be made for newsprint production systems in other Canadian provinces.

Table 6.8: Power mixes and GWP for three Canadian provinces

Province	Fossil (%)	Nuclear (%)	Hydro (%)	GWP (gCO_2/MWh)
Alberta	91	0	9	8.59e+5
Ontario	33	39	28	3.87e+5
Quebec	1	4	95	1.85e+4

Table 6.9: Characterization results using three different power mixes for the electricity production model

Impact category	Unit	Ontario	Quebec	Alberta
Acidification	mol H+	5,3E+02	1,6E+02	1,2E+03
Eco-toxicity	g 2,4-D	7,2E+03	3,8E+02	1,0E+04
Eutrophication	g N	5,6E+02	4,1E+02	7,3E+02
Global warming	g CO_2	1,3E+06	3,9E+05	2,6E+06
Human health cancer	g C_6H_6	1,4E+02	1,6E+01	2,0E+02
Human health criteria pollutants	DALY	2,3E-04	6,4E-05	3,9E-04
Human health non cancer	g C_7H_7	7,5E+05	1,2E+05	1,3E+06
Ozone depletion	g CFC11	2,5E-02	8,9E-03	3,3E-02
Smog formation	g NOx / m	5,1E+00	1,9E+00	1,1E+00

b. Effluent–Oriented Scenarios

For this group of scenarios, impact assessment was basically focused on eutrophication results, since this is the impact category mainly sensitive to nutrient emissions and also because no reliable data were available on the amount of sludges produced from the compared (emerging) alternatives, and the management of these is expected to affect other impact categories. For instance, we know from the literature review that tertiary treatment technology by coagulation/flocculation generates sludges difficult to dewater, which mostly have to be landfilled; this would affect the global warming potential. On the other hand, there are alternatives for the management of the sludges generated by membrane technologies, which can be incinerated. This would affect regional impact categories as well as human health criteria pollutants.

The resulting benefits from the developed scenarios include reduction in the eutrophication potential from 50 to 80% for tertiary treatment and zero effluent, respectively.
Complementarily, we have assessed the ozone depletion potential, due to the increased chemical consumption related to the coagulation/flocculation technology. The resulting ozone depletion potential is 19% higher than in the baseline model. Yet, when a prior water conservation program is applied, the consequent increase is negligible (1%).

c. Additional Scenario

Table 6.10 presents the characterization results for the additional scenario where the alternative of 100% DIP is compared to the one using the energy recovered from the incineration of the additional amount of wastepaper, instead of recycling it.

6.2.4 Assessment of Methodological Choices

a. Allocation Rules: By-Product Allocation Approaches for Sawmill Operations

Table 6.11 shows the characterization results for the production of 1 admt of newsprint using two alternative approaches for by-product allocation in sawmill operations. In general, the alternative approaches do not significantly change the characterization results. When environmental burdens are allocated to lumber and chips, and not to hogfuel (alternative approach 1), the results are the same. When they are allocated only to lumber (alternative approach 2), the results vary from 2% to 13% with respect to the baseline model, with a higher percent of variation for the impact categories where transportation has the higher contributions (i.e., human health criteria pollutants and smog formation), since we are eliminating the log transportation contribution for chips and hog fuel allocated in the baseline model.

b. System Boundaries: Exclusion of Wastepaper Collection

The assessment of the effects of excluding the wastepaper transportation from the curbside to material recovery facilities in cities shows that they are negligible for all the impact categories, since the contribution from this activity is very small (<<1%), the highest one being 0.00435% for human health criteria pollutants.

Table 6.10: Characterization results for additional scenario using three different power mixes for the electricity production model

Impact category	Unit	Ontario			Quebec			Alberta		
		Baseline	100%DIP	55%EW	Baseline	100%DIP	55%EW	Baseline	100%DIP	55%EW
Acidification	mol H+	5,3E+02	3,4E+02	3,8E+02	1,6E+02	1,9E+02	2,2E+02	1,2E+03	6,0E+02	6,5E+02
Eco-toxicity	g 2,4-D	7,2E+03	3,2E+03	3,2E+03	3,8E+02	3,9E+02	2,6E+02	1,0E+04	4,4E+03	4,5E+03
Eutrophication	g N	5,6E+02	4,9E+02	5,5E+02	4,1E+02	4,3E+02	4,8E+02	7,3E+02	5,6E+02	6,2E+02
Global warming	g CO2	1,3E+06	8,2E+05	7,7E+05	3,9E+05	4,3E+05	3,6E+05	2,6E+06	1,3E+06	1,3E+06
Human health cancer	g C6H6	1,4E+02	6,9E+01	6,5E+01	1,6E+01	2,0E+01	1,2E+01	2,0E+02	9,3E+01	9,1E+01
Human health criteria pollutants	DALY	2,3E-04	1,4E-04	1,5E-04	6,4E-05	7,6E-05	8,1E-05	3,9E-04	2,1E-04	2,2E-04
Human health non cancer	g C7H7	7,5E+05	4,0E+05	3,8E+05	1,2E+05	1,4E+05	1,1E+05	1,3E+06	6,3E+05	6,2E+05
Ozone depletion	g CFC11	2,5E-02	1,9E-02	1,4E-02	8,9E-03	1,2E-02	7,3E-03	3,3E-02	2,2E-02	1,8E-02
Smog formation	g NOx / m	5,1E+00	3,5E+00	4,9E+00	1,9E+00	2,2E+00	3,5E+00	1,1E+01	5,8E+00	7,3E+00

Table 6.11: Characterization results for alterative allocation approaches in sawmill operations

Impact category	Unit	Baseline	Alternative approach 1	Alternative approach 2
Acidification	mol H+	3,0E+02	3,0E+02	2,9E+02
Eco-toxicity	g 2,4-D	3,2E+03	3,2E+03	3,1E+03
Eutrophication	g N	4,4E+02	4,4E+02	4,3E+02
Global warming	g CO_2	1,2E+06	1,2E+06	1,1E+06
Human health cancer	G C_6H_6	7,6E+01	7,6E+01	7,4E+01
Human health criteria pollutants	DALY	1,2E-04	1,2E-04	1,1E-04
Human health non cancer	g C_7H_7	3,8E+05	3,8E+05	3,6E+05
Ozone depletion	g CFC11	6,1E-03	6,1E-03	6,0E-03
Smog formation	g NOx / m	2,6E+00	2,6E+00	2,3E+00

CHAPTER 7 – CONCLUSIONS AND CONTRIBUTIONS TO THE BODY OF KNOWLEDGE

Current approaches for the interpretation of results in LCA studies oriented towards process analysis present some shortcomings. They are generally focused on the identification of processes that contribute more to the impact assessment results. Sometimes the category indicators are weighted, adding subjectivity to the analysis, and there is no evidence that an uncertainty or data quality assessment complements this procedure, as recommended by ISO (2001).

In this research project, an alternative approach is recommended. The analysis is focused on model parameters rather than on unit processes, and it not only assesses contributions, but also parameter uncertainty. This integrated analysis allows a more comprehensive interpretation of results. For instance, the results of the sensitivity analyses demonstrate that the indicator for ozone depletion is more sensitive to the uncertainty of some parameters of the chemical production processes than to the parameter of chemical consumption in the newsprint production. Therefore, the consequent recommendation is to improve the data quality before taking any action with respect to chemical consumption in the process. It is impossible to generate this kind of recommendation if we only look at process contributions.

An additional benefit of the proposed approach is the avoidance of valuation elements, which in the first place are still under debate within the LCA community. A best available practice has not yet identified, and the available set of weighting factors does not necessarily represent the context of specific systems, as addressed in this project. Another important benefit is the use of an easy-to-perform and reliable sensitivity analysis technique that does not require information on the probability distribution of the parameter data, which is very difficult to obtain, especially for data collected from secondary sources.

For the illustration of this new interpretation approach, a cradle-to-gate baseline model was developed for the production of 1 admt of newsprint, rigorously following ISO 14040 standards. The methodological choices made during the model development were based on process know-how, previous related works, SETAC guidelines, and ISO standards. They are clearly presented and justified in such a way that they can be used as a reference for similar case studies. Additionally, an assessment of the effects of using alternative approaches for two methodological choices was performed and it was shown that neither the existent alternative approaches for by-product allocation in sawmill operations nor the inclusion of the wastepaper collection transportation significantly affect the baseline model results.

The interpretation of the baseline model results showed that energy consumption and nutrient liquid emissions are the mill process parameters that significantly affect the life cycle environmental performance. Alternative scenarios for the reduction of the impacts caused by these process parameters were developed using current environmental strategies for integrated newsprint mills, including an increase of DIP production, electricity co-generation, tertiary treatment, and zero effluent technologies. The developed alternative mill configurations with increased production of DIP and/or co-generation systems showed important environmental benefits (e.g., 20 - 40% reduction in global warming potential), except for some impact categories (i.e., acidification, smog formation, and human health criteria pollutants) for which the indicator results increased as a consequence of the increased amount of natural gas consumption in the designed configurations. On the other hand, it was demonstrated that the benefits that can be achieved from the energy-oriented scenarios strongly depend on the at-source power mix, which varies according to the mill location. The effluent-oriented scenarios showed significant improvement with respect to eutrophication potential (i.e., a 50-80% reduction), with additional benefits from zero effluent technologies, which completely eliminate the contribution from newsprint mill effluents to eutrophication, optimize water use, and yield alternatives to the landfilling of the generated sludges.

Contributions to the Body of Knowledge

The following are the main contributions to the body of knowledge from this research project, related with the initial stated main hypothesis and sub-hypotheses:

- A proposal of a practical and systematic procedure for the evaluation of model parameters in LCA case studies oriented towards the identification of opportunities for the main production process to improve the life cycle environmental performance.
- The increase of DIP production capacity and the implementation of co-generation at an integrated newsprint mill have important benefits for most environmental impact categories, especially when fossil fuel sources have a significant contribution in the electricity mix.
- The implementation of tertiary treatment and especially of the zero effluent technologies involve significant improvements in the life cycle environmental performance related to eutrophication potential
- When fossil fuel sources have a high contribution in the electricity mix, recycling wastepaper for DIP production or incinerating it in a city cogeneration plant to recover electricity have similar potential benefits. Furthermore, the impacts of wastepaper collection are negligible in comparison to other life cycle stages.

Limitations, Recommendations, and Future Work

The assessment of parameter uncertainties is limited to the data used in the inventory analysis and does not include the effects of the uncertainty on characterization factors, because information on the uncertainty ranges for these factors is not provided in the selected impact assessment method (and most of the current methods do not include this kind of information). If the necessary information becomes available in the near future, it would be interesting to perform these evaluations as part of the interpretation of results.

In the development of the baseline model, the initial set of data quality requirements was not met for some of the parameters, mainly for those related to the production of chemicals. Some of them showed a significant sensitivity to the characterization results. It is recommended to improve the data quality of the baseline model, starting with the large interval uncertainty ranges. An additional sensitivity analysis can confirm whether it is necessary to improve the process-related data as well.

Not all the impact categories relevant to the context of the study were assessed, specifically those related with the abiotic resources and land use, since the assessment models are still under development. However, the inventory data necessary for the assessment have been included. Therefore, the inclusion of these impact categories should be considered when well accepted characterization models become available. A discussion on the criteria used for the model selection should be included as part of the methodology of the impact assessment phase.

The scenario analyses were limited to the modification of the baseline model in order to illustrate its use for the assessment of process variants and to show their potential benefits. The methodological elements for comparative LCA studies (e.g., the use of marginal technologies) and the additional interpretation checks on the scenario results were not performed. Furthermore, the analysis of effluent scenarios was limited to the eutrophication impact category, due to the lack of reliable data on the amount of sludges generated from the studied technologies, which are expected to affect various impact categories. Future modifications for the comparative use of the baseline model require taking into account these limitations. These issues can be improved by the inclusion of the necessary data for a comprehensive assessment, the application of the methodological elements for consequential LCA studies, the transparent inclusion of optional LCA elements (i.e., valuation) in order to assess the scenarios trade-offs among impact categories, and the interpretation of the scenario results to assess the effects of additional uncertainties (i.e., the methodological choices made during the scenario development, the definition of valuation factors, etc.).

Finally, the results obtained in this study and the consequent conclusions are only valid for the system studied and no generalization at can be made based on the analyses performed. This is mainly due to the influence of the electricity model, which varies among newsprint mills, on the impact assessment results.

Future work using the developed baseline model can be oriented towards the analysis of process variants and the investigation of emerging LCA process applications, such as the demonstration of continuous environmental improvement in environmental management systems, the assessment of major process modifications as a complement to the classical environmental impact studies, and the design of a minimum impact mill configuration.

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APPENDICES

APPENDIX A: DEVELOPMENT OF AN LCA BASELINE MODEL FOR NEWSPRINT PRODUCTION

Development of an LCA Baseline Model for Newsprint Production

Erica Salazar[1], Réjean Samson[2] and Paul R. Stuart[1]

École Polytechnique de Montréal, Department of Chemical Engineering
C.P.6079, succ. Centre Ville, Montréal, Québec, Canada H3C 3A7

1. NSERC Environmental Design Engineering Chair in Process Integration
2. CIRAIG (Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services)

Corresponding author: paul.stuart@polymtl.ca

Abstract:

Goal, Scope and Background: This publication presents a methodology for the development of an LCA baseline model for newsprint. The model was created for the following future LCA applications: establishing improved metrics for continuous environmental improvement, assessing major process modifications of existing plants, and for strategic planning including the investigation of minimum impact manufacturing configurations. These applications are part of an overall program whose theme is "Life Cycle Thinking in the Pulp and Paper Industry", and which is oriented towards illustrating the use of LCA as an engineering tool for the environmental analysis of process variants.

A recent survey of LCA applications in the pulp and paper industry has shown that LCA use is evolving from traditional applications such as paper and non-paper product comparisons, to process analysis for the comparison of technical options. The survey also showed that most published case studies present incomplete LCA methodologies with respect to ISO 14040 standards, especially for the interpretation elements.

The baseline model developed in this study includes rigorously all ISO 14040 elements, and has been formally peer-reviewed by LCA experts. This publication is intended to explain the impact of various methodological choices made during the study. We subsequently propose a systematic interpretation procedure oriented towards the identification of improvement opportunities related to environmental performance and data quality.

Methods: The system boundaries defined were cradle-to-gate, including all the processes involved in the production of 1 admt of standard newsprint, from raw material extraction to newsprint distribution; the functional unit was defined as 1 ton of newsprint with 10% moisture content (termed an air-dried metric ton or admt). Primary data were used for the unit processes having major contributions, and secondary data were used for background systems having less significant contributions. The system was modeled with commercial software SIMAPRO version 5.1, and TRACI was used as the characterization method for the life cycle impact assessment. For the interpretation of results, a systematic procedure was developed based on a sensitivity analysis of category indicator results involving both foreground parameters (those over which the company has direct control) and background parameters (those over which the company has no direct control). The sensitivity of two methodological choices on the characterization results was assessed in detail.

Results and Discussion: Twenty six parameters were identified as potentially having a critical impact on the LCA results, and were investigated using sensitivity analysis. A comparison of the sensitivity results were carried out making the distinction between foreground and background parameters.

Among the foreground parameters, the sensitivity results show that most of the impact categories have significant sensitivity (>10%) to energy consumption at the newsprint mill, including electricity and natural gas consumption. However, eutrophication showed significant sensitivity only to total nitrogen (N-t) emissions in the wastewater effluent.

Among background parameters, sensitivities higher than 20% were found for data on ozone-depleting emissions from EDTA production (a chelating agent used in the process), arsenic emissions to water (from soda production), mercury and arsenic emissions to air (from electricity production), and methane emissions (from industrial landfill). The impact categories most affected by these parameters were global warming, ozone depletion, ecotoxicity and human toxicity.

Conclusions: A methodology for developing an LCA baseline model for use in the analysis of process variants was illustrated for the case of newsprint production. The intended applications were the basis for the definition of methodological choices, and for the interpretation of the impact assessment results. The systematic procedure used for the interpretation of results included a reliable sensitivity analysis technique that avoids constraints involved in the use of optional impact assessment elements, such as normalization and weighting, and avoids the need for sophisticated and time-demanding uncertainty assessments. The simplicity of this systematic approach is advantageous for its practical application in any attributional LCA, especially for those oriented towards the analysis of process variants.

Recommendations and Outlook: It was determined that the most important factors involved in improving the life cycle environmental performance of newsprint production are the reduction of electricity and natural gas consumption, and of nitrogen emissions in the effluents. The environmental strategies that can be investigated in this context might include increased deinked pulp production which is less energy intensive than mechanical pulping processes and involves other life cycle benefits (e.g. less newspaper to landfills), electricity cogeneration from woodwaste, as well as the implementation of tertiary effluent treatment or zero effluent technologies.

Keywords: life cycle thinking, attributional LCA, pulp and paper industry, newsprint production, process variants, data quality, sensitivity analysis.

Introduction

Life Cycle Thinking is being promoted among different sectors for the analysis of product chains and improved environmental decision-making. This concept implies that the impacts of all life cycle stages be comprehensively considered when making informed decisions on production and consumption patterns, policies, and management strategies (UNEP 2003).

A recent survey of LCA studies in the pulp and paper industry (Gaudreault et al. 2004) has shown that there is an evolution in applications from traditional product comparison (e.g., paper vs. plastic bags) to process analysis (e.g., emissions assessment along the paper cycle), comparison of technical options (e.g., wastepaper management options) and, to a lesser extent, strategic evaluations (e.g., long-term process planning, supply chain structuring). The survey showed that most case studies presented incomplete LCA methodologies when compared to ISO 14040 standards. Around half of them were limited to the inventory analysis phase, and most studies did not present interpretation checks.

Seven years ago, the Canadian Pulp and Paper Association developed a voluntary environmental profile program in response to market demands for detailed environmental information on the environmental burdens associated with the life cycle of their products. The objective of the program was to provide environmental product information to customers through an Environmental Profile Data Sheet or EPDS (Terrachoice 1997). The EPDS contains information about the life cycle inventory of the production phase and specific indicators of upstream processes (e.g. sustainable forestry practices, energy use for key bleaching chemicals), two impact categories (global warming and acidification), non-LCA elements such as risk assessment (e.g. effluent toxicity characteristics), and environmental management systems.

The "Life Cycle Thinking in the Pulp and Paper Industry" program at École Polytechnique de Montréal is oriented towards the use of LCA baseline model as an engineering tool to analyze process variants. Specifically, the following applications are being investigated in the program:

- Demonstration of continuous environmental improvement in the context of Environmental Management Systems,
- Assessment of major process modifications in the context of Environmental Impact Studies, and
- Investigation of the minimum impact manufacturing configurations in the context of strategic process planning.

New LCA-based continuous environmental improvement metrics related to process operations will be developed by comparing the results of the baseline model for mill process data from different years. For the two latter applications, LCA is to be used as a comparison tool in order to assess the environmental benefits and impacts due to the transition of the baseline process to the designed mill configurations.

The baseline model presented here was rigorously developed based on the ISO 14040 elements, and has been formally peer-reviewed by LCA experts. This publication illustrates the applied methodology and focuses on the details of methodological choices based on the study objectives and context. Moreover, a systematic model evaluation procedure is proposed for the sensitivity analysis of foreground parameters (those over which the company has direct control) and background parameters (those over which the company has no direct control), in order to identify improvement opportunities for environmental performance and data quality, respectively.

1 Description of the System Studied

The system studied is the production of standard newsprint with 20% recycled pulp content. The main production chain includes woodlands, a sawmill and a newsprint mill. These operations are managed by the same company and are located in Northern Ontario, Canada. Figure 1 depicts the system.

Spruce (softwood) and aspen (hardwood) are produced in the woodlands. The raw material used for newsprint production is spruce, which represents 75% in volume of the total woodland production. Aspen is used for plywood production. During winter, softwood logs are transported an average distance of 80 km to the sawmill, by truck.

Sawmill operations convert the logs to lumber as the main product, and chips are generated as a co-product, while bark and shavings (i.e. hog fuel) are produced as wood wastes. Lumber is a finished product sold to the construction industry. Chips are used to produce wood pulp in a thermo-mechanical pulping (TMP) process, while hog fuel is burned at the boiler house in order to produce the steam necessary for the newsprint production process (primarily for drying). The sawmill is co-located with the newsprint mill, and provides around half of the chips and hogfuel necessary for the newsprint production process. The remainder is supplied by local sawmills.

The TMP process has a yield of 95% (dry mass of pulp produced relative to the dry mass of chips supplied). The TMP refining stage consumes most of electricity required for newsprint production, but part of this energy is recovered as steam. Due to the high temperature of chip refining, some volatile wood compounds are evaporated during this process. These VOC emissions are partially recovered in the heat recovery unit, and the rest are discharged to the atmosphere.

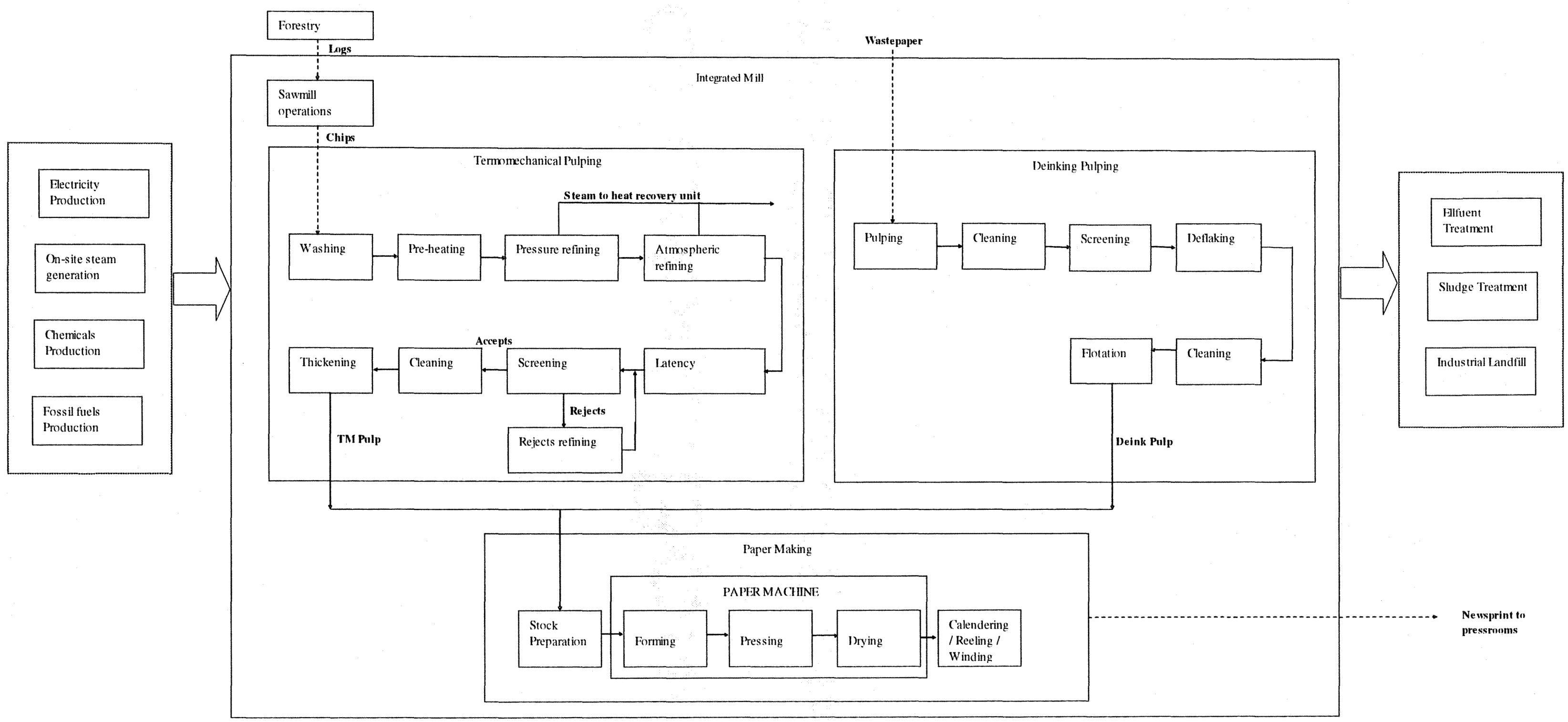

Figure 1: Cradle-to-gate life cycle of newsprint production

Recycled pulp is obtained from old newspapers (ONP) and old magazines (OMG) by the deink pulp (DIP) process. Wastepaper furnished to the DIP process is purchased mainly from Ontario or the USA, and transported to the newsprint mill by truck or rail. DIP yield is around 85% (dry mass of pulp produced relative to the dry mass of wastepaper supplied) due to wastepaper contaminants such as dirt, tramp metal, adhesives, coatings, and ink. Part of the solid waste by-products can be burned in the boiler house to produce steam.

Pulp produced by the TMP and DIP processes is furnished to four paper machines where newsprint is manufactured. A significant amount of steam is required for newsprint drying, and most of the water eliminated from the pulp is recycled to the process. The paper machines at the mill also produce a specialty paper product derived from TMP pulp called Uncoated Groundwood Specialty (UCGS), but in much smaller quantities (around 15% of the total yearly tonnage).

The steam required at the mill is produced from natural gas and biomass (i.e., woodwaste and sludges from DIP and effluent treatment processes) combustion in the boiler house. The main emissions from the boiler house include combustion gases with associated particulate matter, as well as boiler ash which is landfilled on site.

The wastewater effluents from the processes receive both primary (i.e., gravity separation) and secondary (i.e., biological) treatment before being released to the receiving waters. The main emissions considered after treatment include BOD (i.e., biochemical oxygen demand), TSS (i.e., total suspended solids), and nutrients (i.e., nitrogen and phosphorus). Other waterborne emissions emitted in lesser proportion include metals (i.e., Zn, Mn, Cd and Cu) and organics (i.e., methanol, chloroform, toluene and phenol). The primary and secondary sludge produced by the effluent treatment plant are mixed with those from the DIP process and then dewatered. Around half of the dewatered solid waste is burned in the boiler house, and the remainder is landfilled on-site.

Most of the electricity consumed in the newsprint production process is purchased from the grid and its average source in Ontario is the following: 33% fossil (from coal), 39% nuclear, and 28% hydroelectric. The main fuels used in the process are natural gas for steam production and diesel for transportation. The chemicals employed in the pulping process include sulphur dioxide, chelants, soda, sodium silicate, borol, hydrogen peroxide, soap, calcium chloride, coagulants and flocculants. Finally, the produced newsprint is distributed to newspaper printing facilities in Ontario, Quebec, and US cities by truck or rail.

2 Methodology Employed for the LCA Baseline Model Development

2.1 Functional Unit and System Boundaries Definition

The system functional unit employed in this study was the production of 1 admt (i.e., 1 air dried metric ton, 10% moisture content) of newsprint. The system boundaries included processes from wood extraction at the woodlands to newsprint distribution (i.e., from cradle-to-gate).

It was assumed that newspaper printing, use, and disposal could be excluded from the study because newsprint production process variants do not significantly affect the environmental impacts due to these stages. For instance, an increase in the recycled content of newsprint can affect the printability and appearance properties of newspapers in pressrooms, and consequently, more ink can be required (Smook 1992). However, these effects were considered negligible compared to those involved with the process modification.

The transportation of raw materials to the mill (i.e., logs, chips, hog fuel, and waste paper) was included in the study. Wastepaper transportation from curbside to material recovery facilities (i.e., wastepaper collection) was initially excluded and due to the existing debate about the impact of this activity in the newsprint life cycle, this initial choice was validated in the interpretation phase when it was found that effectively its contribution in all the impact categories is negligible (<1%). Chemical transportation to the newsprint mill was excluded since they are negligible in comparison (Terrachoice 1997).

2.2 By-Product Allocation

Volume-based allocation was applied in the woodlands, and mass-based allocation was applied in sawmill and paper machines, following recommendations by Jungmeier et al. (2002b). Environmental burdens allocated to aspen, lumber, and UCGS were excluded from the system since they are not used for newsprint production.

2.3 Data Sources and Data Quality Requirements

Both primary (i.e., site specific) and secondary (i.e., from commercial databases) data sources were used for the baseline model. Following ISO 14041 (ISO 1999), primary data were used for the processes that contribute most of the mass and energy flows in the system and have significant environmental emissions (i.e., woodlands, sawmill, newsprint mill, and electricity production). These processes were modeled using average data from the year 2001. Chemicals, fuel production, and landfill were modeled using commercial databases. The following data quality requirements were initially set for the baseline model:

- **Time**: The year of inventory collection is 2001. Data from the previous five years (1995 – 2000) were preferred.

- **Geography**: The system under study is located in Northern Ontario. North American data were preferred.
- **Technology**: Average technology was preferred.

However, the available databases only met these criteria for fuel production (i.e., Franklin database: American average 1995 – 1999). For chemical production, European databases were used (i.e. IVAM and BUWAL: European averages 1990 – 1994; and KCL-ECO: Finnish averages 1992). In the case of chemicals for which no specific databases were available (e.g. chelants, coagulants, flocculants, and other polymers) general databases were used instead (e.g., chemicals organic ETH: European averages 1990 - 1994). Landfill models were also based on a European database (i.e. KCL-ECO). The effect of the gaps between the initial data quality requirements and the quality of data actually used in the base line model was assessed at the interpretation phase.

The databases mentioned above are included into two LCA softwares, namely SIMAPRO 5.1 and KCL 3.0. The former has the advantage of including most of the databases and therefore it was selected for the construction of the baseline model. On the other hand, KCL 3.0 only includes the KCL-ECO database that has the advantage of being exclusively related to pulp and paper industry. Thus, the data selected from this latter database was imported to the model on SIMAPRO.

2.4 Selection of Impact Categories, Category Indicators and Characterization Models

Selection of impact categories, category indicators, and characterization models was performed according to the objectives and context of the LCA study. The selection was based on SETAC best available practices, which are ISO compatible (Udo de Haes et al. 1999a). Table 1 summarizes the results of this process.

Input-related impact categories (i.e., biotic and abiotic resources, land use) were not included in the study for the following reasons:

- The impact of biotic resources is not relevant since the wood resources used in the system (i.e. spruce) are from man-controlled cultures and are therefore not expected to be depleted (Udo de Haes et al. 2002), and
- Best available practice has not been yet identified for input-related impact categories (Udo de Haes et al. 2002).

In the case of land use, available methods were reviewed (Weidema 2001; Lindeijer et al. 2002). However, the lack of specific data for the activities related to the system studied made it difficult to characterize this impact. Nonetheless, inventory data were included in the baseline model in order to analyze results at the inventory level and incorporate appropriate models when they become available.

The output-related impact categories recommended by SETAC were included in the study (Udo de Haes et al. 1999b). Global impacts for global warming and ozone depletion were modeled at midpoint level using the International Panel on Climate Change (IPCC, time horizon: 100 years) and the World Meteorological Organization (WMO, time horizon: infinite), respectively.

Regional impacts were modeled at midpoint level using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method from the United States Environmental Protection Agency. This method was selected because it includes the spatial differentiation in fate and sensitivity recommended by SETAC (Udo de Haes et al. 1999b), and because the potentially important influence of release location upon the strength of expected impact has been demonstrated (Norris 2003; Hauschild et al. 2003). Furthermore, TRACI incorporates other SETAC recommendations to improve the environmental relevance of the midpoint indicators, such as the distinction of phosphorus and nitrogen limiting conditions for eutrophication at the continental level, the relative influence of NOx ambient concentrations, and the differentiation between different VOCs in photochemical smog (Udo de Haes et al. 1999b; Norris 2003). Characterization factors developed for Michigan were used in this study since this is the nearest state to the mill location, and can be considered a good approximation when comparing averages of meteorological conditions that are important in the evaluation of regional impacts (i.e. temperature, precipitation, wind speed).

For local impacts, TRACI models were also selected. Ecotoxicity, human health cancer, and human health non cancer were modeled at midpoint level using multimedia fate modeling for US average conditions, while human health particles were modeled at endpoint level (Bare at al. 2003). Michigan was again selected as the reference state for the characterization factors. TRACI models for these impacts show compatibility with SETAC recommendations regarding the use of midpoint toxicity indicators for species composition for terrestrial and aquatic ecosystems, and the division of human health impacts into disability-type subcategories (Udo de Haes et al. 1999b).

Table 1: Selected impact categories, indicators and characterization models

Impact Categories	Category Indicators	Characterization Models
Climate change	G CO_{2eq}	IPCC
Ozone depletion	g $CFC11_{eq}$	WMO
Acidification	mol $H+_{eq}$	TRACI – Michigan
Eutrophication	g N_{eq}	TRACI – Michigan
Photo-oxidant formation	g NO_{xeq}/m	TRACI – Michigan
Eco-toxicity	G $2{,}4D_{eq}$	TRACI – USA
Human health-cancer	G C_6H_{6eq}	TRACI – USA
Human health-non cancer	G C_7H_{7eq}	TRACI – USA
Human health criteria pollutants	DALY	TRACI – Michigan

2.5 Main Simplifications and Assumptions in the Inventory Analysis and Impact Assessment

Sawmill Model

Off-site sawmills supply around 30% of the chips and 40% of the hog fuel consumed by the newsprint mill, and the remainder of these raw materials is provided by the on-site sawmill. For this study, the sawmill model was developed using data only from the on-site sawmill, assuming that the technology involved is representative of that employed at the off-site sawmills. It was verified that electricity and steam consumptions are similar for the local sawmill suppliers and the on-site sawmill. The fuel breakdown in the newsprint mill boiler house might not be representative of the local sawmills, however this difference was considered negligible since the steam consumption by the sawmills is only 5% of the total steam consumption of the system.

Transportation Models

Round trips were assumed for the transportation of logs, and fuel consumption was based on primary data. One-way trips were assumed for the transportation of chips, hog fuel, wastepaper supply, and newsprint distribution; the return was not included for these materials because typically, cargo from other companies or systems is transported during the return trip. Fuel consumption was based on mass transported (tonnes or number of loads) and average distances, using the fuel efficiency factors (L/km or L/t-km) for trucks and locomotives recommended in the EPDS guidelines (Terrachoice 1997). Air emissions were calculated based on fuel consumption levels, using emission factors from the references recommended in the EPDS guidelines (Terrachoice 1997). In the case of particles, they were based on input from the Franklin database, sourced on the USEPA AP-42 MOBILE model.

Particle Size Distribution

Human health effects from particulate emissions strongly depend on particle size. Particles that are smaller than 10 μm in diameter (i.e., PM10 or inhalable particles) can penetrate into the lungs, furthermore particles 2-3 μm and smaller (i.e., PM2.5 or respirable particles) are able to reach the lung alveoli. This fact becomes more concerning if we consider the fact that smaller particles are more complex chemically and present greater opportunities for surface adsorption of toxic substances and subsequent deposition in the lungs (Health Canada 2003).

The selected model for human health particles (i.e. TRACI) includes characterization factors for TSP, PM10 and PM2.5; however, information on particulate size distribution is often not included in commercial databases. Therefore, the following assumptions and models were applied in order to calculate the particulate size distribution for these processes:

- **Natural gas pre-combustion and combustion**: All particulate emissions from natural gas combustion are smaller than 1 μm (USEPA 1998). In the natural gas production process, particulates are emitted from compressor engines that fire natural gas (USEPA 1995a); therefore, the same particulate size distribution is used.
- **Diesel pre-combustion**: The size distribution for industrial boilers firing residual oil (USEPA 1995b) was used. In the diesel production process, there are also particulate emissions from the cracking processes. Due to lack of information about the size distribution of this operation, distribution for industrial boilers was considered representative for the whole process.
- **Transportation road/rail**: The size distribution for diesel vehicles (USEPA 2003) was used.

Emissions data from processes with small contributions to the particulate inventory per 1 admt of newsprint (i.e., chemical production as well as gasoline, propane, and kerosene combustion and pre-combustion) were not refined by including the size distribution.

CO_2 Emissions from Biomass Combustion

There is a debate among life cycle practitioners about whether or not to include CO_2 emissions from biomass combustion in the inventory analysis, especially when comparing two alternative energy sources (Reijnders et al. 2003). In this case study, the neutral approach recommended by the International Council of Forest and Paper Association was employed. This approach, which is compatible with most international protocols including that of the IPCC, is based on the assumption that CO_2 emitted from biomass combustion is the atmospheric CO_2 that was sequestered during growth of the tree; hence, there is no net contribution to the atmospheric CO_2 level (NCASI 2001).

Total Suspended Solids (TSS) Characterization

TSS refers to the amount of fiber and other suspended matter in pulp and paper mill effluents, and it is regulated by the Canadian Pulp and Paper Effluent Regulations under the Fisheries Act (Environment Canada 2003). TSS is not characterized by existing life cycle impact assessment models. Due to its associated biological nature, it has assumed that TSS impacts are already accounted for by BOD characterization in the eutrophication impact category. Furthermore, a comparison of the data on the TSS emissions from the newsprint mill with the current Canadian regulation showed that the load of TSS discharged after wastewater treatment is small enough that the impact from its settling in the receiving waters can be assumed negligible.

Organic Load Characterization

The TRACI eutrophication model includes separate characterization factors for BOD (Biochemical Oxygen Demand) and COD (Chemical Oxygen Demand) and recommends characterizing only COD when both parameters are available for any unit processes (Norris 2003). This recommendation was applied in all the unit processes of the system studied except the newsprint mill, because the mill effluent characteristics (i.e. low biodegradability of the total suspended solids) correspond to those for which the consideration of COD would lead to a significant overestimation of the total environmental oxygen demand (Norris 2003).

2.6 Discussion on Optional Impact Assessment Elements

Normalization

Two references recommended by ISO (ISO 2001a) were evaluated for normalizing the characterization results in order to better understand the relative magnitude of the impacts from newsprint production. However, the lack of representative data needed for normalization limited the effective application of this technique in this study.

- **Baseline scenario for the system under study**: The average cradle-to-gate life cycle of newsprint production in the North American context would be the best reference scenario for this particular case study. However, this is not yet available.
- **Emissions per capita**: Data to calculate the normalization factors for this reference are available; however, some data gaps exist for significant emissions from the system (e.g., BOD), which prevented the calculation of a representative normalization profile.

Weighting

The question of weighting of impacts arises when trade-offs among impact categories are necessary for the objectives of the LCA study (i.e., when it cannot be unambiguously decided that one process option is environmentally preferable to another without the summation of impact categories). This optional step was therefore not applied in this study, but will eventually be necessary for the intended applications of the baseline study.

Various weighting methods are covered in the literature, and it has been shown that they may lead to different results. At this time, there is no single favored weighting method for use in LCA (Udo de Haes et al. 2002; Hofstetter 1999; Finnveden 1999). For case studies involving the definition of the weighting factors, the process to determine them must be transparent and a sensitivity analysis should be performed in order to illustrate the effects of choices made. Furthermore, the weighted profile should be considered as one input to the interpretation phase as opposed to the final answer (Bengtsson et al. 2000).

2.7 Peer Review Process

A formal internal peer review of this case study has been carried out by LCA experts from the Interuniversity Reference Centre for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services (CIRAIG) at the Ecole Polytechnique de Montreal, following ISO protocols (ISO 1997). This peer review included the methodology for each of the four LCA phases as well as the calculation procedures, input data, and results.

3 Methodology for Interpretation of Results

3.1 Definition of the Interpretation Objectives and Approach

The objective of the interpretation phase has been stated as "to evaluate the study in order to draw conclusions, explain limitations and give recommendations based on the inventory analysis and impact assessment results" (ISO 2001b). However, the type of conclusions sought from the study depends on the intended application, and therefore the approach used for interpretation must be based on the eventual application. For instance, Heijungs proposes different numerical steps depending upon whether one or more products are assessed. For one-product assessment, when the purpose is usually the identification of improvement opportunities, three numerical analyses are proposed: contribution, perturbation, and uncertainty (Heijungs et al. 2001).

A review of published attributional LCA case studies shows that the identification of opportunities to improve environmental performance (i.e. "hot spots identification") is usually based on the contribution of weighted profiles, calculated using weighting factors that do not necessarily reflect the context of the study. Furthermore, the sensitivity of the results to the weighting factors is often not addressed (Nielsen et al. 2002; INFRAS 1998). When not using weighting factors, LCA case studies are limited to the comparison of one impact category, for example global warming (Wiegard 2001; Pickin et al. 2002).

For the assessment of parameter uncertainty, the current practice also presents some limitations. There is still a lack of consensus about how these issues should be handled (Bjorklund 2002) and, as a consequence, these analyses have been typically been excluded from LCA studies. In a recent survey of thirty case studies, it was found that only three of them included some sort of uncertainty assessment (Ross et al 2002). The Monte Carlo simulation has been recommended to assess the inaccuracy and representativity of inventory data (Huijbregts et al 2001; Maurice et al 2000; Huijbregts 1998b); however, in practice, it is difficult and time-consuming to obtain the probability distributions necessary for this kind of assessment, and their estimations introduce additional uncertainty to the analysis.

In this study, we propose a new approach for the identification of improvement opportunities for both the environmental performance and the quality of inventory data, using sensitivity analyses. This approach is based on the fact that models are sensitive to input parameters in two distinct ways:

- The high correlation of model results with an input parameter (i.e., a sensitive parameter), so that small changes in the input value result in significant changes in the output; and
- The uncertainty associated with an input parameter (i.e., an important parameter), which is propagated through the model and contributes to the overall output uncertainty.

An important parameter is always sensitive because otherwise the parameter variability would not appear in the output, whereas a sensitive parameter is not necessarily important because it may have low uncertainty, adding little variability to the output (Hamby 1994).

We can relate this distinction between type of parameters when using LCA to assess production processes. The foreground parameters (e.g., electricity consumption at the mill, sludge generation from de-inking process, etc.) usually have low uncertainty because they are obtained from the production site, but at the same time, they can have a significant impact on the category indicator results. These parameters must be identified and considered when defining mill configurations with an improved life cycle environmental performance and when planning major process modifications. The background parameters (e.g., air emissions from electricity production, liquid emissions from the production of chemicals used in the de-inking process, etc.) usually have higher uncertainty than the foreground ones since they are obtained from commercial databases or literature references. Although the mill does not have direct control over them, their identification is useful in order to focus attention on the parameters that contribute most to the uncertainty of category indicator results, so that they can be prioritized when improving the data quality of the LCA model. An additional objective of the interpretation phase is to assess the uncertainties due to methodological choices (e.g., allocation rules). This can also be accomplished by the use of sensitivity analysis.

3.2 Identification of Key Parameters

A large number of parameters are introduced in the life cycle inventory phase, depending on the scope and complexity of the system under study. Therefore, it is important to systematically select the key parameters on which the interpretation analysis will be focused.

A broad sensitivity analysis using standard uncertainty estimates has been recommended (Sakai et al. 2002; Heijungs et al. 2001; Heijungs 1996). However, a disadvantage of using a standard sensitivity range is that parameters with a minor contribution to LCA outcomes but with a large unknown uncertainty range are eliminated from the analysis beforehand (Huijbregts 1998b). An alternative approach is to identify the key input parameters based on the contribution of input data to the results and a qualitative assessment of the data uncertainty (Maurice et al. 2000).

This approach was applied in this study for each category indicator result. Contributions from unit process/emission pairs were calculated with the aid of the LCA software and the corresponding parameter uncertainty was assessed using Data Quality Indicators (DQI). The DQI matrix proposed by Weidema (1998) was used for this purpose. Table 2 presents the indicator matrix. Note that the data source indicator was added to Weidema's original work and descriptions for the scores were defined according to the characteristics of the various data sources used for this study. For the assessed parameters, the DQI was calculated as the average of the assigned scores for each indicator as proposed by Maurice et al. (2000).

Table 2: DQI matrix used for the assessment of parameter uncertainty in the selection of key parameters

Indicator / Score	1	2	3	4	5
Data source	Average of continuous measurements	Average of punctual measurements	Calculated from measured data	Calculated from literature references	Estimated
Temporal correlation	<3 years old	<6 years old	<10 years old	<15 years old	>15 years old or unknown
Geographical correlation	From area under study	From larger area in which the area under study is included	From area with similar production conditions	From area with slightly similar production conditions	From unknown area or area with very different production conditions
Technological correlation	From processes and enterp. under study	From processes under study but from different enterprises	From processes under study but from different technology	From related processes but from same technology	From related processes but from different technology

The selection of "key" and "perhaps key" parameters was performed based on Heijungs' approach that establishes the relationship among contribution, uncertainties and key parameters in LCA studies. This approach is illustrated in Figure 2. For this purpose, the limit between low and high uncertainty was defined as a DQI of 2 and the one between low and high contribution as 10% based on Maurice's work.

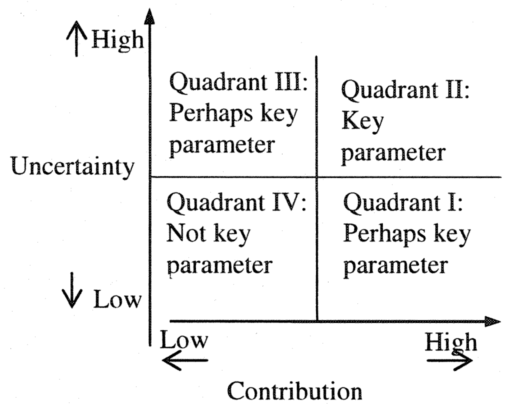

Figure 2: Identification of key parameters according to their contribution and uncertainty (Heijungs 1996)

The detailed procedure of key parameter selection is explained below, and is illustrated with the example of Global Warming (GW).

Step 1: Calculate the contribution per substance and focus the subsequent analyses only to those substances that significantly contribute to the category indicator results. For instance, select a group of substances which contribute altogether in more than 99% to the category indicator results. **Ex**: Among thirteen greenhouse gases (GHG) included in the study, 99.2% of the total GW indicator result is contributed by CO_2 (90.2%) plus CH_4 (9%).

Step 2: Calculate the contribution of unit processes on the total emission of each substance selected in step 1. **Ex**: Table 3 shows the contribution of unit processes to total CO_2 emission.

Table 3: Unit process contributions to total CO_2 emission

Unit process	Contribution (%)
Electricity production	79
Natural gas combustion[1]	12
Transportation	6
Fuel production	2
Chemical production	2

[1]For the generation of process steam in the boiler house

Step 3: Calculate the contribution of each unit process/emission pair to the category indicator result by multiplying the contributions calculated in steps 1 and 2. **Ex**: Table 4 shows the contribution of unit processes on the total GW potential due to CO_2 and methane emissions. (Only contributions higher than 1% are shown in this table).

Table 4: Contribution of unit process/emission pairs on total GW potential

Unit process	Emission	Contribution (%)
Electricity production	CO_2	71
Natural gas combustion	CO_2	10
Industrial landfill	CH_4	8
Transportation by truck	CO_2	4
Natural gas production	CO_2	1

Step 4: Calculate the DQI for the unit process/emission pairs with contributions over 1%.

Ex: Table 5 shows the assigned scores to the unit process/emission pairs presented in Table 4 as well as the calculated average DQI.

Table 5: DQI calculation for unit process/emission pairs with contributions over 1%

Unit process	Emission	Data source	Temporal correlation	Geographical correlation	Technological correlation	Average DQI
Electricity production	CO_2	3	1	1	1	1,5
Natural gas combustion	CO_2	4	1	2	2	2,3
Industrial landfill	CH_4	3	3	3	5	3,5
Transportation by truck	CO_2	4	3	2	2	2,8
Natural gas production	CO_2	3	1	3	2	2,3

Step 5: Select as key parameters those that contribute to more than 10% and have a DQI greater than 2. **Ex**: The emission of CO_2 from natural gas combustion to produce steam at the boiler house was selected as a "key parameter".

Step 6: Perform a selection of representative "perhaps key parameters" based on their contribution to the total category indicator results, a quantitative indicator that is more certain than the DQI. DQIs can be used as secondary criteria for the selection. For instance, when equal contributions are found for two different unit process/emission pairs, the one with the higher DQI would be selected. **Ex**: The parameter "CO_2 emissions from electricity production" was selected from quadrant I, while the parameter "methane emissions from industrial landfill" was selected from quadrant III.

Step 7: For all the selected parameters, identify the elementary and intermediate flows that affect them. The sensitivity of the results on these latter parameters is analyzed in the next phase of the interpretation procedure. **Ex**: Table 6 shows the list of the selected unit process/emission pairs with the related elementary and intermediate flows, as well as their units.

Table 6: Key parameters for the sensitivity analysis of global warming potential (GWP) results

Unit process (emission)	Type of Flow	Parameter	Unit
Electricity production (CO_2)	Intermediate	Electricity consumption	kWh/admt
	Elementary	CO_2 from electricity production	kg/kWh
Natural gas combustion in boiler house (CO_2)	Intermediate	Natural gas consumption	m^3/admt
	Elementary	CO_2 from natural gas combustion	kg/m^3
Industrial landfill (CH_4)	Intermediate	Process wastes to landfill	kg/admt
	Elementary	Methane from landfill	kg/kg

3.3 Definition of Uncertainty Ranges for Selected Key Parameters

Uncertainty ranges for selected key parameters were calculated in order to perform the sensitivity analyses. The guidelines proposed by Maurice et al. (2000) were used for the calculation or estimation of the uncertainty ranges, as follows:

- For primary data from the woodlands, sawmill and newsprint mill, the minimum and maximum values of monthly statistics for the year 2001 defined the uncertainty range.
- For primary data from electricity production, where only averages were available from the production site, the assumption of ±20% for continuous measurements and ±50% for punctual measurements was applied (Hanssen et al. 1996).
- For secondary data from the Franklin database: Different percentages of variation were applied based on information from the database developers.

- For secondary data from other databases where no information on uncertainty was available, the uncertainty range was based on a comparison of similar processes from different databases.
- For secondary data where no information on similar processes from other databases was available, the uncertainty range was based on the large intervals proposed by Finnveden et al. (1998).

3.4 Sensitivity Analysis on Key Foreground and Background Parameters

The sensitivity analysis technique was selected from a study where fourteen methods were compared in terms of the required calculation effort, the results for parameter sensitivity ranking, and the relative method performance (Hamby 1995). The study concluded that the Sensitivity Index (SI) is "the easiest and most reliable method that can be performed without detailed knowledge of the parameter distribution". The sensitivity index is a method where one parameter is varied at a time from its minimum to its maximum value (uncertainty range) while the others are held fixed, and the resulting output percent difference is calculated. The sensitivity index is expressed by the equation:

$$SI = \frac{D_{\max} - D_{\min}}{D_{\max}} \quad \ldots (1)$$

where D_{min} and D_{max} represent the minimum and maximum output values, respectively, resulting from varying the input over its uncertainty range (Hamby 1994).

Sensitivity Indexes (SI) were calculated for the selected key parameters and the results were analyzed separately for the foreground (Figure 3) and background parameters (Figure 4), in order to identify improvement opportunities on environmental performance and data quality, respectively. Twenty six key parameters were analyzed in total, but only those with SI higher than 10%, in the case of foreground parameters, and 20%, in the case of background parameters, are shown. It can be observed that the background parameters in general show higher sensitivity than the foreground parameters due to their higher uncertainty.

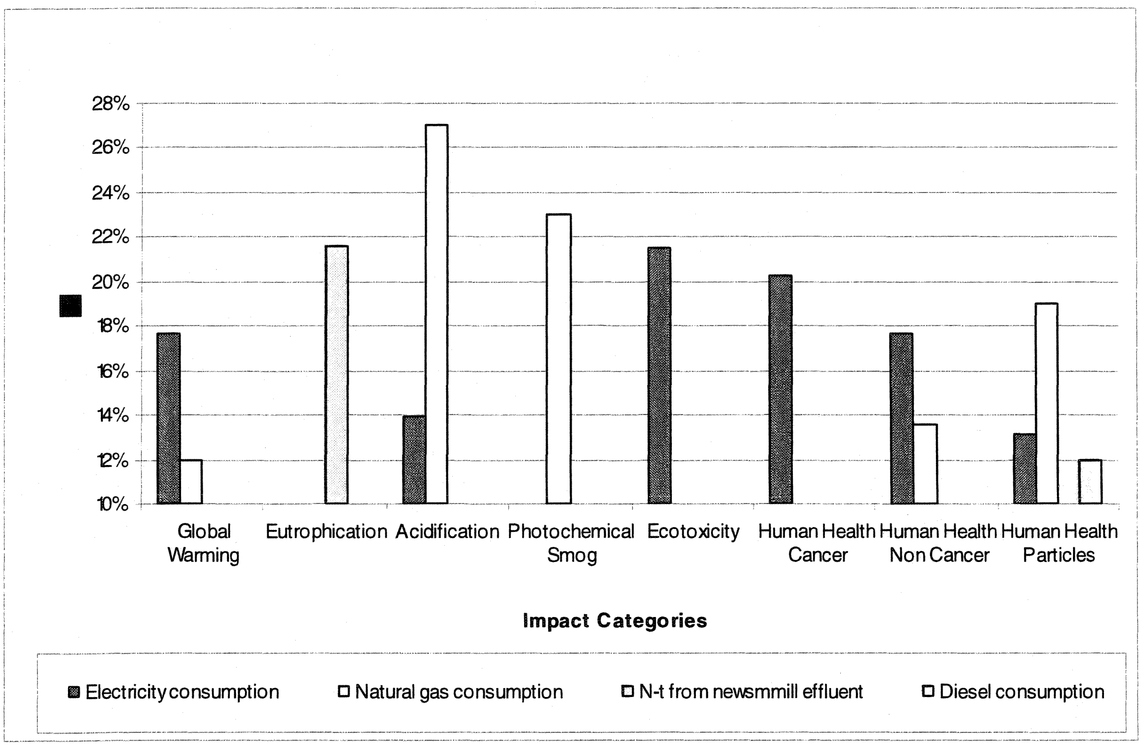

Figure 3: Results of sensitivity analysis on foreground parameters

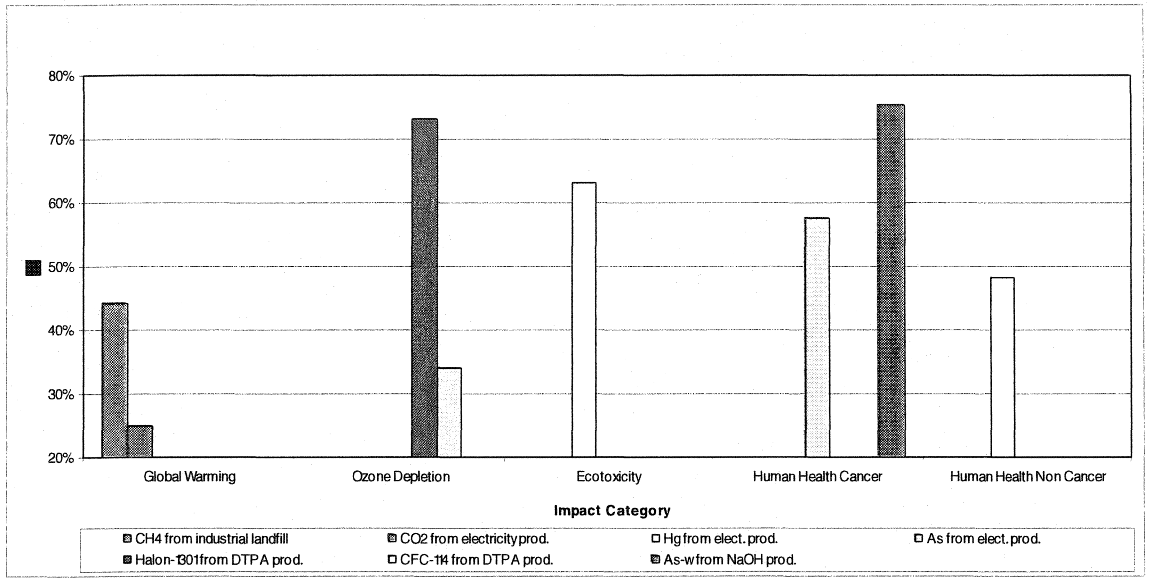

Figure 4: Results of sensitivity analysis on background parameters

From Figure 3, it can be concluded that the mill efforts to improve the life cycle environmental performance of the newsprint production should be focused on energy issues, especially on the consumption of electricity and natural gas to produce steam, since they show high sensitivity in most of the impact categories. Current environmental strategies to handle these issues include increasing DIP production, which is less energy intensive than the TMP process, as well as co-generating steam and electricity from biomass. Potential eutrophication can be significantly decreased by reducing N-t emissions from the newsprint mill effluents. Strategies that can be considered in this regard include tertiary treatment and technologies leading to zero effluent operation.

From Figure 4, it can be concluded that efforts to improve the data quality should be focused on the ozone depleting emissions from EDTA (i.e. chelant) production, arsenic emissions to water from soda production, mercury and arsenic emissions to air from electricity production, and methane emissions from industrial landfill. These actions should be first oriented towards improving the estimated uncertainty ranges, and then evaluating if better production data quality is required.

3.7 Assessment of Uncertainties due to Methodological Choices

Examples of methodological choices that introduce uncertainty to LCA models include: the selection of functional unit, the system boundaries, the allocation rules, the choice of using marginal or average data, and the selection of characterization methods (Bjorklund 2002). In order to reduce this type of uncertainty, recommendations include the use of standardized procedures (i.e. ISO 14040 family), and of peer review processes when choices are judged (Huijbregts 1998a). In the development of the baseline model, the recommended measures to reduce the uncertainty due to choices were employed. Furthermore, the effects of two methodological choices, for which there is a debate among LCA practitioners, were analyzed.

By-Product Allocation in Sawmill

In the case of sawmills, there is debate about whether to consider chips and especially hog fuel as co-products (Jungemeier et al. 2002a). According to ISO, for processes with outputs that can be partially co-products and partially wastes, the environmental burdens can be allocated only to co-products (ISO 1999). In this case study, environmental burdens were allocated not only to lumber but also to chips and hog fuel, based on the production mass; this approach was selected because newsprint production depends on chips and hog fuel to address fiber and energy requirements, respectively. The effects of alternative allocation approaches (detailed below) debated in the literature were assessed by modifying the baseline model including these alternative approaches and normalizing the consequent results against those from the baseline model. The comparative results are presented in Figure 5:

- Alternative approach 1: the environmental burdens are allocated to lumber and chips. Hog fuel is considered as a waste; therefore no environmental burden is allocated to it.
- Alternative approach 2: the environmental burdens are allocated only to lumber, since this is the main product.

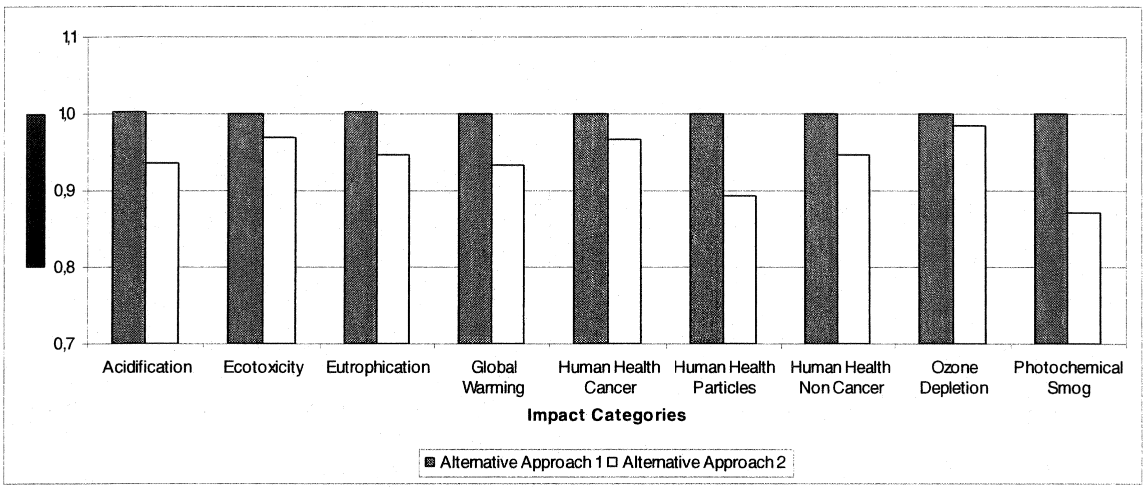

Figure 5: Results of sensitivity analysis on alternative allocation approaches for sawmill operations

The results show that the allocation of environmental burdens to hog fuel does not affect the final impact assessment results; note that for all the impact categories, the normalized value is equal to one, which means that is the same as in the baseline model. However, when environmental burdens are exclusively allocated to lumber, there is a 2% to 13% difference between the characterization results and the baseline model results. The highest values are for human health particles and photochemical smog, since transportation is a significant factor, and the diesel used for the woodland and sawmill operations represents around 75% of the total diesel consumption for transportation by truck.

Exclusion of Wastepaper Collection

During the scope definition, transportation of wastepaper from curbsides to material recovery facilities in the cities was assumed to be negligible when compared with other transportation activities (i.e., log transportation, wastepaper transportation from material recovery facilities to the mill, etc.) and therefore excluded from the system. During the interpretation phase, this assumption was verified by using the municipal waste truck model from the IVAM database and average data on the rate of old newspaper collection during the year 1998 in the province of Ontario. The results show that the contribution of wastepaper collection is negligible for all the impact categories (<<1%), the highest one being 0.00435% for human health particles.

4 Conclusions

Current approaches for the identification of improvement opportunities in LCA studies present some disadvantages due to the exclusion of uncertainty and data quality assessments. This is especially true when weighting factors are introduced in the analyses, adding subjectivity to the drawn conclusions.

In this study, an alternative procedure is proposed. Firstly, it is focused on model parameters rather than on unit processes, but most importantly it complements the contribution analyses with assessment of parameter uncertainty. This integrated analysis allows a more comprehensive interpretation of results as well as more reliable and coherent conclusions. Additional benefits include the avoidance of valuation elements and the use of an easy-to-perform and reliable sensitivity analysis technique that does not require information on probability distributions.

The practical application of the proposed approach is illustrated with a real case study of the production of 1 admt of newsprint from cradle to gate. The development of this case study was based on process know-how, previous related works, SETAC guidelines, and ISO standards; the main assumptions and methodological choices are explained in this publication and that they can be used as reference for similar case studies.

Applying the proposed procedure to this case study, energy consumption and nitrogen water emissions were identified as the mill process parameters that significantly affect the environmental performance of the entire production chain. On the other hand, the comparative analysis of sensitivity results for background parameters resulted in higher sensitivity values for ozone depleting air emissions from EDTA production (i.e., halon and CFC-114), air emissions of Hg and As from electricity production, methane air emissions from landfill and water emissions of As from NaOH production. Therefore, efforts to improve the inventory data quality should be primarily focused on these parameters.

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APPENDIX B: IDENTIFYING ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES FOR NEWSPRINT PRODUCTION USING LIFE CYCLE ASSESSMENT (LCA)

Identifying Environmental Improvement Opportunities for Newsprint Production Using Life Cycle Assessment (LCA)

Erica Salazar[1], Réjean Samson[1], Ken Munnoch[2] & Paul R. Stuart[1]

1. Department of Chemical Engineering, École Polytechnique de Montréal, C.P.6079, succ. Centre Ville, Montréal (Qc), Canada
2. Tembec - Spruce Falls Inc., 1 Government Road, P.O. Box 100. Kapuskasing (On), Canada

* **Corresponding author** (paul.stuart@polymtl.ca)

Abstract

The goal of this study was to use LCA for the systematic identification and assessment of opportunities to improve the environmental performance of newsprint production, accounting for a wide range of potential impacts. An LCA baseline model for the production of 1 admt newsprint from 80% TMP and 20% DIP was developed (Salazar et al, 2004) which included processes from wood extraction to newsprint distribution (i.e., cradle-to-gate), following ISO 14040 standards and then peer-reviewed by other LCA experts. The model results were subsequently interpreted in order to identify opportunities for improvements in the product chain environmental performance.

The addition of additional DIP production capacity and the implementation of co-generation at the integrated newsprint mill were examined in the context of energy consumption. Other than in a few cases, it was found that important benefits could be achieved in the product chain for most environmental impact categories (and in particular, 20-40% reduction in Global Warming Potential was achieved). Related to mill effluent quality, tertiary treatment prior to discharge by alum-polymer coagulation/flocculation was examined, as well as the mill modifications necessary to achieve zero effluent operation based on membrane technology. In this case, the eutrophication potential impact category showed a significant reduction of 50-80%.

Also, the importance of the power mix or fuel source for power generation (which varies with mill location) on the baseline model results was shown. Finally, an evaluation of the alternatives of recycling wastepaper for DIP production, or incinerating it in a city cogeneration plant to recover electricity showed greater environmental benefits when fossil fuel sources have a high contribution in the electricity mix.

Introduction

LCA is a method which can assess the potential environmental impacts associated with a product, process, or service along its entire life from resource extraction to ultimate disposal (i.e., cradle-to-grave). The LCA methodology was recently standardized by the International Organization for Standardization (ISO) 14040 series, and consists of the following phases: goal and scope definition, inventory analysis (LCI), impact assessment (LCIA), and interpretation. Figure 1 shows the relationship between these four phases and general LCA applications (ISO 1997). The double arrows illustrate the iterative nature of the methodology.

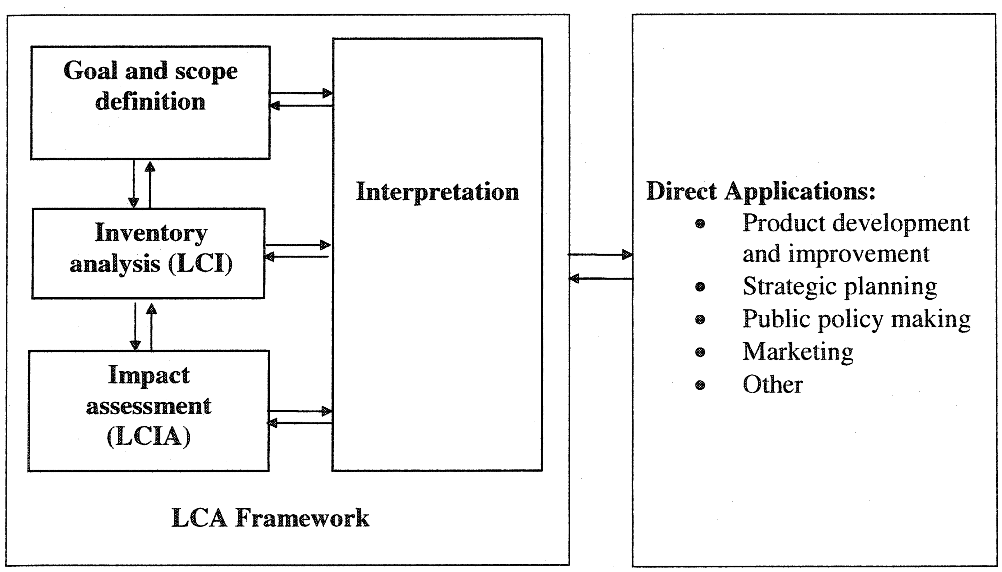

Figure 1: Phases of LCA (ISO 1997)

The LCA study goal defines the purpose of the study as well as its intended application, while the LCA study scope defines the extent of the study and contains a description of the system. In the inventory phase, data on the environmental interventions or stressors (e.g., emissions, resource usage) related to each process included in the scope of the study are collected and expressed per functional unit (e.g., kg SO_2 per ton of product). Data can be obtained from the production site and suppliers (called primary data) or from LCA databases on standard inputs such as those related to purchased chemicals and fossil fuels (called secondary data). The inventory calculation is not always straightforward because in practice, many industrial processes result in more than one product (e.g., lumber), and intermediate or final products are recycled as raw materials (e.g., woodwaste), and decisions must be made about how to allocate environmental burdens to each output. The purpose of the impact assessment phase is to determine the relative importance of each environmental intervention in the inventory phase by aggregating them into a set of impact categories. Finally, the interpretation step serves to evaluate the study results in order to draw conclusions, explain limitations, and give recommendations. The results of this last phase may lead to an adjustment of the goal and scope or to further investigations of the inventory and associated impacts (Hertwich et al. 2002).

As with any process analysis tool, LCA has its benefits and limitations. LCIA is fundamentally an analysis of inputs and outputs to the environment rather than an analysis of the actual environmental consequences or effects from a system. Impact Assessment modeling in LCA involves in some cases highly simplified assumptions about complex environmental processes (e.g., eco-toxicity) and there are also assumptions for dealing with spatial, temporal, and dose-response issues. This is why some authors recommend complementing LCA results with other analysis techniques (e.g., risk assessment, Owens 1999). Other limitations of the methodology include the uncertainty of the results due to data gaps, data uncertainties, methodological choices, and values. However, this is similarly the case with other environmental tools (Finnveden 2000).

A recent survey (Gaudreault et al. 2004) showed that LCA applications in the pulp and paper industry have evolved from traditional product comparison (e.g., paper vs. plastic bags) to process analysis (e.g., emissions assessment along the paper cycle), comparison of technological options (e.g., wastepaper management options), and, to a lesser extent, strategic evaluation (e.g., supply chain structuring). Another important finding of this survey was that most of the published case studies presented incomplete LCA methodologies; around half of them were limited to the inventory analysis phase and most of them did not present the interpretation checks. Nonetheless, an improvement in the completeness of the studies was identified in the most recent publications, probably as a consequence of the methodology standardization by ISO.

Study Objectives

"Life Cycle Thinking" is being increasingly considered by the pulp and paper industry. This concept implies that the impacts of all life cycle stages are systematically considered when making decisions on changes in process configuration, company policies, and overall management strategies. The most effective strategy for applying Life Cycle Thinking concepts is by using LCA for the assessment of process variants.

The objectives of this study were to illustrate Life Cycle Thinking by completing a systematic LCA for newsprint production, including the following:

- To show how Life Cycle Assessment (LCA) can be used to examine the newsprint production chain in order to assess its potential overall environmental impacts,
- To show the critical mill processes and non-process parameters which have a significant influence on the environmental impacts of the product chain,

- To use LCA to assess relevant process variants which impact the defined parameters, by comparing the existing mill model with modified mill process configurations (i.e., process variants).

This LCA baseline model for newsprint production is to be used for the following applications in other ongoing work: for the demonstration of continuous environmental improvement in the context of Environmental Management Systems, for the assessment of major process modifications in the context of Environmental Impact Studies, and for the investigation of the minimum impact mill configuration in the context of mill strategic planning.

Overall LCA Methodology Employed

The most important methodological choices and the assumptions and simplifications made during the baseline model development, as well as the procedure followed for the interpretation of the baseline model results, are presented in Salazar et al. (2004).

The functional unit in the LCA was defined as the production of 1 admt of newsprint. The system boundaries include the production chain from wood extraction to newsprint distribution (cradle-to-gate). Figure 2 summarizes the system boundaries.

For the inventory analysis, primary data for the processes with major contributions was used (i.e., data for the integrated mill and electricity production), while secondary data was used for the background systems having less contribution (i.e., data for fuel and chemicals production, industrial landfill). A previous Environmental Profile Data Sheet (EPDS) developed by the mill for information purposes was the starting point for modeling the life cycle inventory. The system was modeled using the LCA software SIMAPRO 5.1, and selected the impact categories relevant to the study based on SETAC guidelines, using the characterization factors developed by the USEPA (i.e., TRACI impact assessment method) in order to characterize the emissions from the system. Table 1 presents the selected impact categories, indicators, and models for this study. Finally, based on the interpretation results, mill alternatives to improve the life cycle environmental performance were identified.

Table 1: Selected impact categories, category indicators and characterization models

Impact Categories	Scale	Category Indicators	Characterization Models
Climate change	Global	g CO_{2eq}	IPCC
Ozone depletion		g $CFC11_{eq}$	WMO
Acidification	Regional	mol $H+_{eq}$	TRACI – Michigan
Eutrophication		g N_{eq}	TRACI – Michigan
Photo-oxidant formation		g NO_{xeq}/m	TRACI – Michigan
Eco-toxicity	Local	g $2,4D_{eq}$	TRACI – USA
Human health-cancer		g C_6H_{6eq}	TRACI – USA
Human health-non cancer		g C_7H_{7eq}	TRACI – USA
Human health criteria pollutants		DALY	TRACI – Michigan

Definition of Newsprint System Addressed by LCA

Standard newsprint production from an integrated TMP/DIP mill is the system under study. The main production chain elements (i.e., woodlands, sawmill, and newsprint mill) are located in Northern Ontario and managed by the same company. Furnish includes 75% spruce and 25% aspen, by volume. During winter, spruce logs are transported to the mill by trucks, while aspen is sold for plywood and therefore is not included as part of the system. Lumber is produced at the on-site sawmill and is sold for the construction industry, and this product is thus also excluded from the system. The on-site sawmill provides approximately 70% of the chips furnish to TMP, and 55% of the hogfuel burned at the boiler house. Additional chips and hog fuel required to cover the mill needs are purchased from local area sawmills and transported by truck.

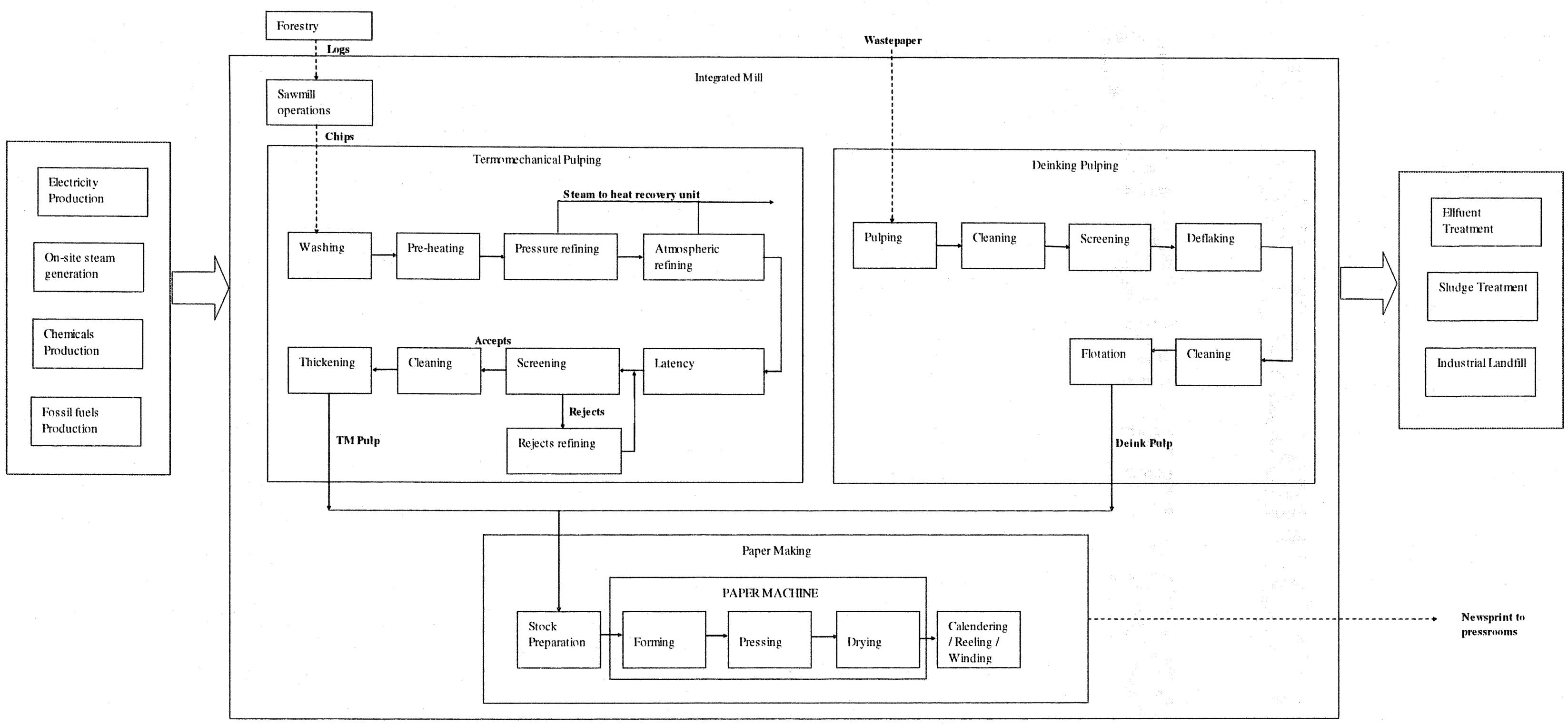

Figure 2: Definition of System Boundaries for Newsprint Production LCA

The TMP yield is around 95%. 70% of the total electricity at the mill is used in TMP refining, of which a part is recovered as steam, which constitutes 20% of the total amount of steam consumed at the mill. The secondary fiber furnished to the DIP process includes Old Newspaper (ONP) and Coated Groundwood Specialty (CGS), which are purchased mainly from Ontario and the USA and transported to the mill by truck or rail. The DIP process yield is around 85%. TMP and DIP pulps are furnished to four paper machines at a ratio of approximately 4:1 to produce standard newsprint. This newsprint is distributed to Ontario, Quebec, and several US cities by truck and rail.

Steam for the process is produced on-site from hog fuel (44%), natural gas (48%), and sludge (8%). Approximately 70% of the process steam is consumed by the paper machines. The mill wastewater is treated in a primary clarifier and an activated sludge treatment plant, and the sludges are combined with those from DIP for dewatering. 50% of the dewatered sludge is burned in the boiler house and the rest is landfilled on-site. Almost all the electricity consumed at the mill (around 98%) is purchased from the grid, for which the at-source power mix is 33% fossil fuel (coal), 39% nuclear, and 28% hydro.

LCA Baseline Model for Newsprint

Inventory Analysis

Figures 3, 4 and 5 present respectively the inventory results for greenhouse gas emissions (GHG), other gases, and particulates. Figure 3 shows that CO_2 is emitted in much higher amounts than methane or N_2O. Most of the CO_2 (79%) is emitted from electricity production, however it should be noted that data for GHG emissions from electricity production were collected in terms of CO_{2eq}. For methane and N_2O, the direct mill emissions present more important contributions: 88% of the methane is emitted from industrial landfill and 55% of N_2O from biomass combustion at the boiler house.

Figure 4 shows that there is less variability in the amount of gases emitted compared to the GHG results. SO_2 is the gas emitted in the highest amount, mainly from electricity (57%) and fuel (38%) production. CO and NO_x are emitted almost in equal amounts; their main contributors are biomass combustion (43% of CO) and electricity production (45% of NO_x). VOCs are emitted in the lowest quantity, mainly from fuel production (69%), while the contribution from thermomecanical pulping is very small in comparison.

Figure 5 shows the inventory results for particulate emissions. The contribution of electricity production is the most important for TSP (60%) and PM_{10} (52%). However, for $PM_{2.5}$, which of some concern due to their inhalability, the contribution from transportation becomes more important (45%) than that from electricity production (32%). The combustion of biomass at the boiler house is the third most important contributor with around 10% of TSP and PM_{10}, and 16% of $PM_{2.5}$.

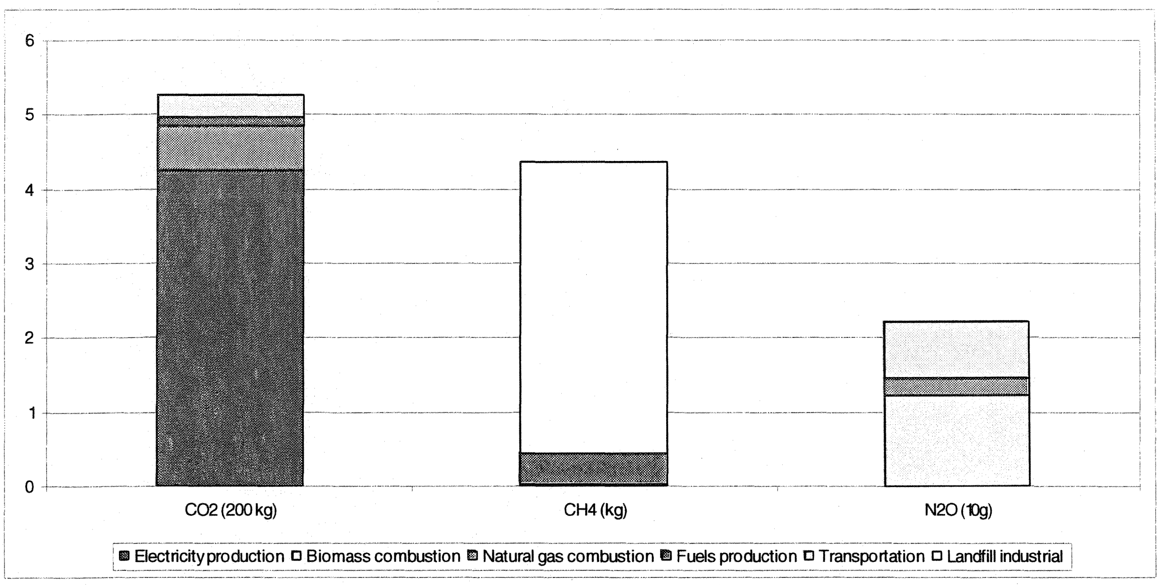

Figure 3: GHG emissions per 1 admt of newsprint

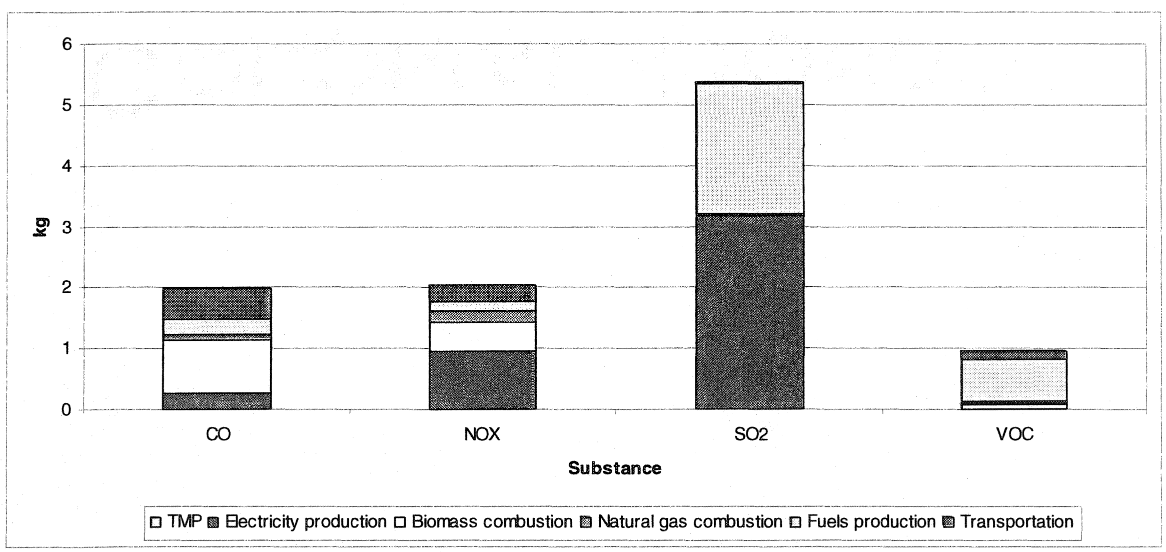

Figure 4: Gas emissions per 1 admt of newswprint

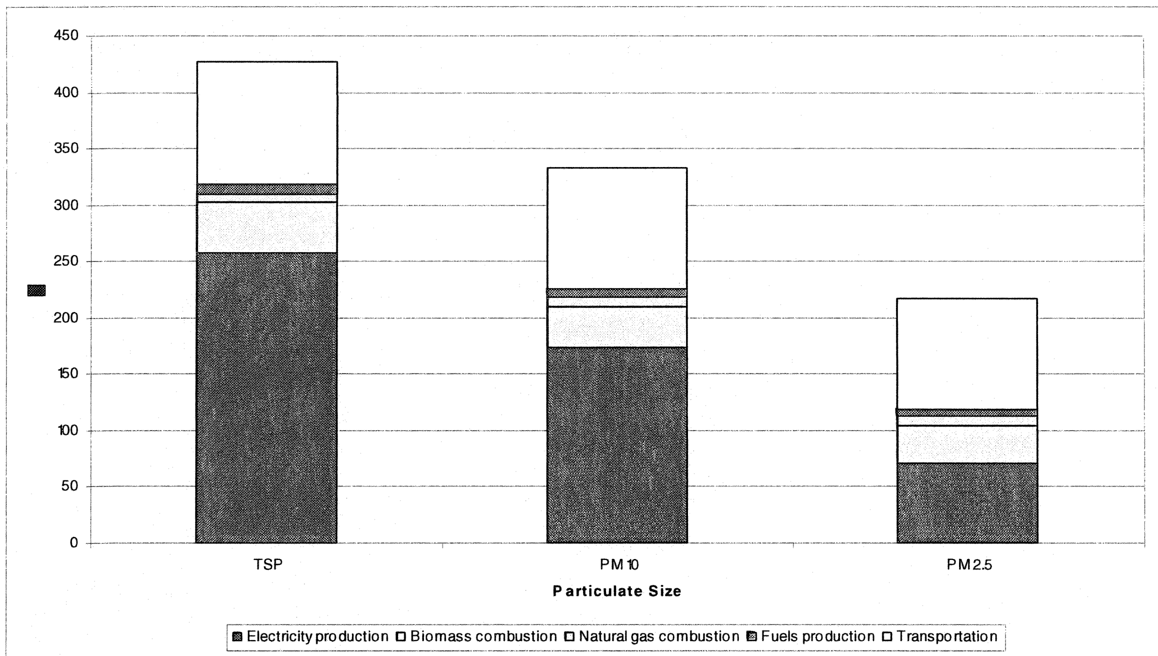

Figure 5: Particulate emissions per 1 admt

Figures 6, 7, 8, and 9 show the following water emissions, respectively, for solids, organic load, nutrients, and metals.

Figure 6 shows the major sources for suspended solids being from the newsprint mill (65%) and, to a lesser extent, from electricity production (33%). Fuel production contributes significantly to the dissolved solids result (93%). Figure 7 shows the results for two organic load indicators: BOD_5 and COD. Around 99% of the organic load (for both indicators) is discharged from the newsprint mill. Indirect emissions are shown separately and among the indirect emitters, fuel production has the highest contribution. Figure 8 shows the nutrient load, expressed with two indicators, N-t and P-t. As in the case of the organic load, the major contribution comes from newsprint production (99% of N-t and 93% of P-t). The second major contributor of P-t emissions is electricity production (7%). Figure 9 shows the most significant metals in terms of mass (>1 g/admt). Newsprint production represents the highest contribution (around 98%) for the natural wood constituents Zn and Mn, while for the rest of the metals, the major contributor is chemicals production.

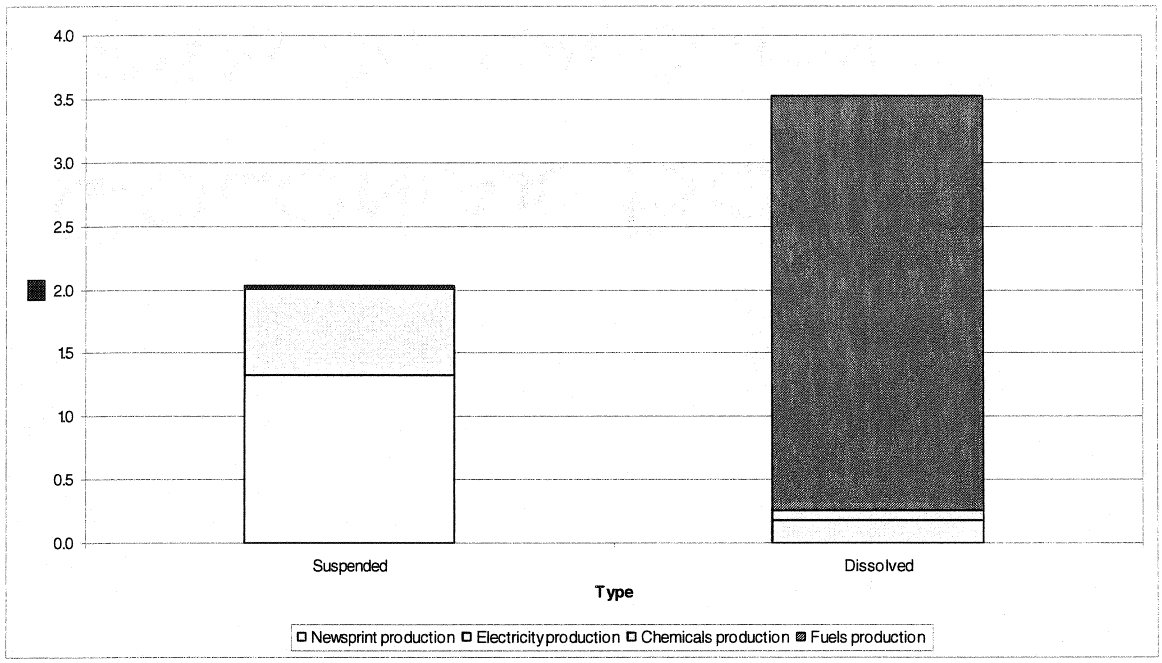

Figure 6: Solid emissions to water per 1 admt of newsprint

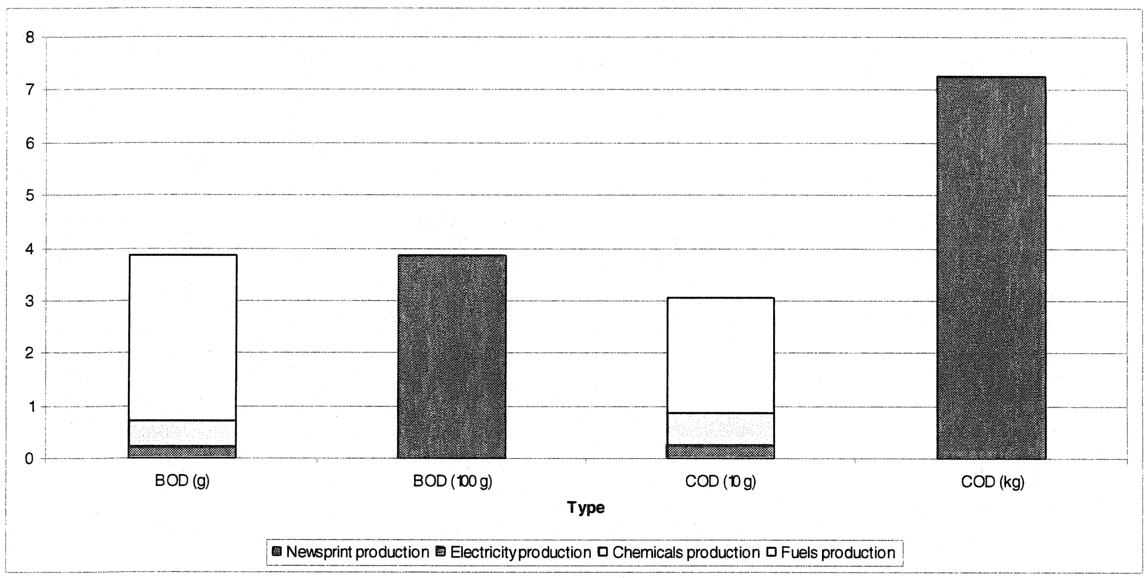

Figure 7: Organic load to water per 1 admt of newsprint

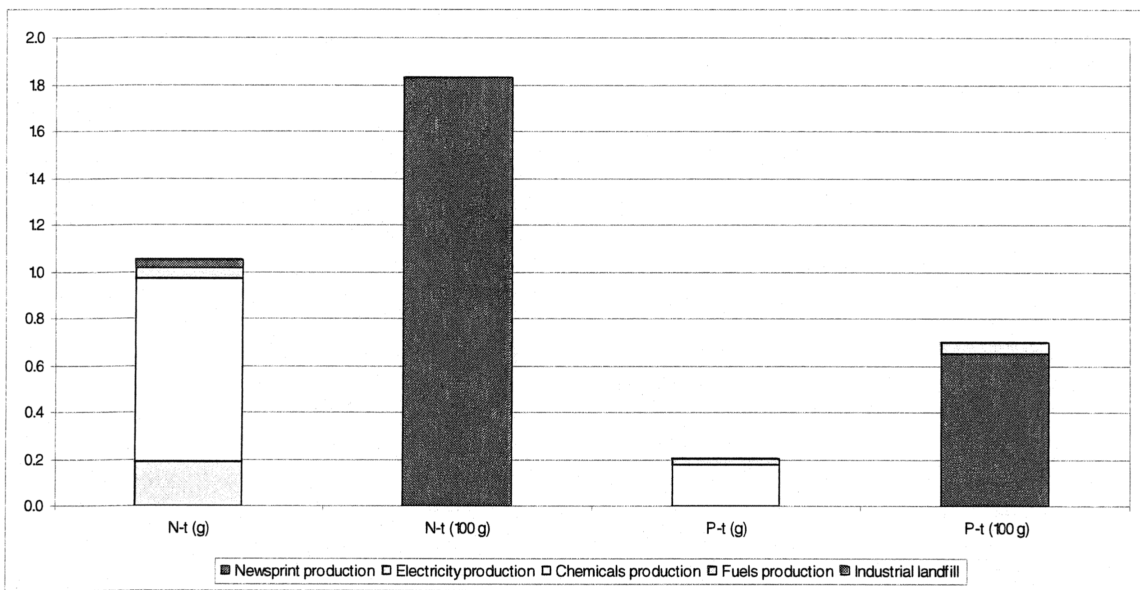

Figure 8: Nutrient load to water per 1 admt of newsprint

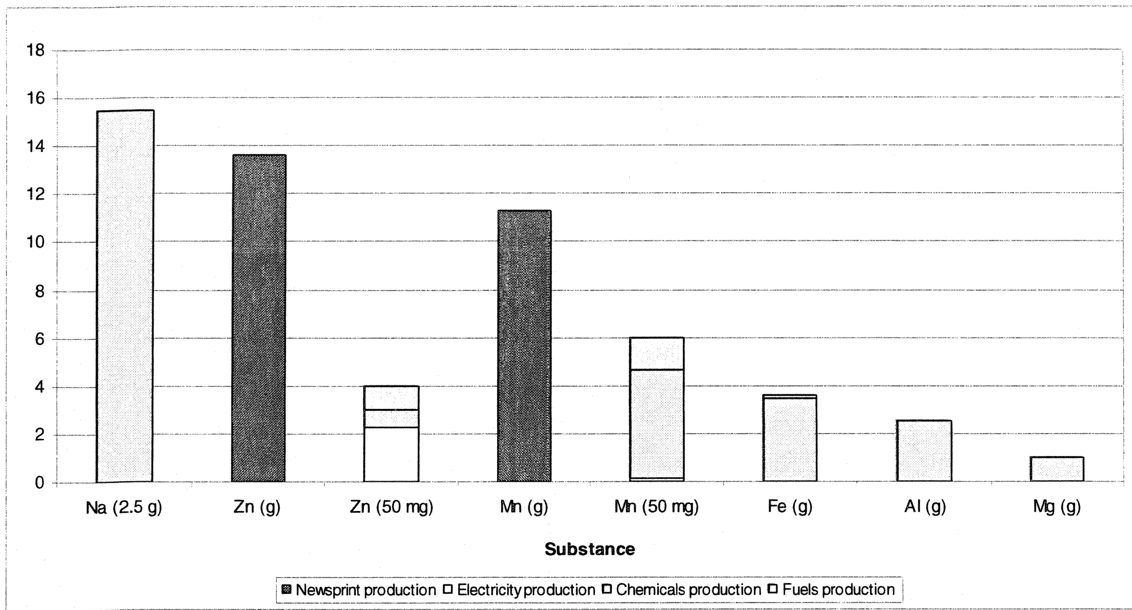

Figure 9: Metal emissions to water per 1 admt of newsprint

Impact Assessment

Table 2 shows the impact assessment results for the impact categories presented in Table 1. The large number of inventory indicators has been reduced to 9. However, since these categories have been evaluated using different indicators, it is impossible to make comparisons among the results without using valuation elements. Therefore, the systematic and careful interpretation of these results becomes critical for the use of LCA in decision making.

Table 2: Category indicator results

Impact Categories	Category Indicators	Total
Climate change	g CO_{2eq}	1.20e+6
Ozone depletion	g $CFC11_{eq}$	6.07e-3
Acidification	mol $H+_{eq}$	3.05e+2
Eutrophication	g N_{eq}	4.36e+2
Photo-oxidant formation	g NO_{xeq}/m	2.64e00
Eco-toxicity	g $2{,}4D_{eq}$	3.20e+3
Human health-cancer	g C_6H_{6eq}	7.61e+1
Human health-non cancer	g C_7H_{7eq}	3.76e+5
Human health criteria pollutants	DALY	1.20e-4

Key Parameters

During the interpretation phase, a sensitivity analysis was completed in order to identify the model parameters on which the category indicator results are most sensitive. The model parameters over which the mill has direct (i.e., foreground parameters) or indirect control (i.e., background parameters) were analyzed. The details of the interpretation methodology are presented in Salazar et al. (2004).

The Sensitivity Index (SI) is defined as:

$$SI = \frac{D_{max} - D_{min}}{D_{max}} \quad \ldots (1)$$

where D_{min} and D_{max} represent the minimum and maximum output values resulting from varying the input over its uncertainty range (Hamby 1994).

Figure 10 shows that the main opportunity for improving the life cycle environmental performance of newsprint production is in the reduction of energy use, especially through electricity and natural gas use, which show significant sensitivity in most of the impact categories. Potential eutrophication can also be significantly reduced by decreasing N-t emissions from the newsprint mill effluent.

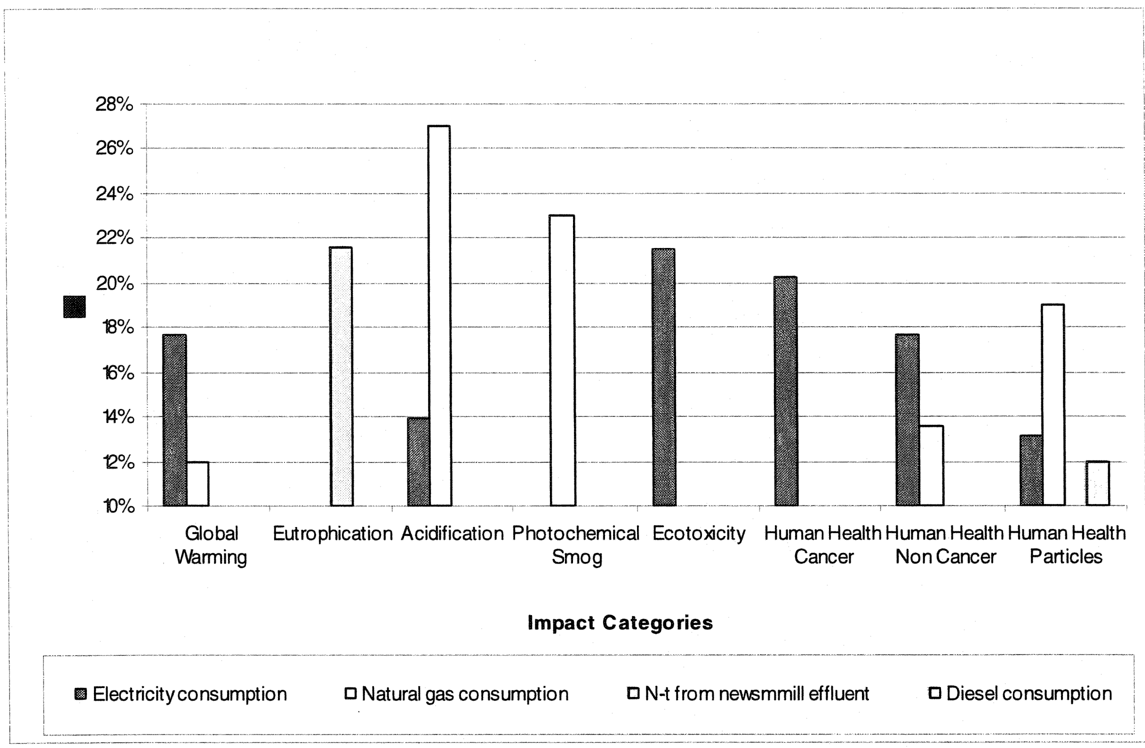

Figure 10: Results of sensitivity analysis on foreground parameters

Scenario Analyses

Energy Management Scenarios

The energy-oriented scenarios are focused on reducing purchased electricity and natural gas consumption, following the sensitivity analysis results. The following strategies were considered:

- Reducing the consumption of electricity by increasing DIP production and lowering TMP production,
- Reducing the amount of energy purchased from the grid by co-generating steam and electricity, preferentially from biomass,

- Implementing a combination of these two strategies.

Based on these strategies, three alternative mill configurations were developed, which are presented in Table 3.

Table 3: Alternative mill configurations to reduce energy consumption and the consequent impacts

Parameter	Units	Baseline	100% DIP	100% CE	100% CE + 100% DIP
DIP content	%	20	100	20	100
Energy Consumption (electricity + steam)	GJ/admt	16	12	36	21
Electricity Breakdown					
Purchased from the grid	%	98	98	0	0
Co-generated on site	%	2	2	100	100
Breakdown of energy sources to produce steam					
Natural Gas	%	48	50	73	54
Hog Fuel	%	44	32	24	36
Sludge	%	8	18	3	10

Note: 100% DIP: Recycling content of the produced newsprint is increased to 100%

100% CE: 100% of the electricity used in the mill is co-generated on-site

The increase in DIP production (100% DIP) results in a consumption of around one half of the electricity required in the base case mill. At the same time, there is a 35% increase in steam production requirement by the boiler house to replace the steam previously recovered from the TMP process. The main assumptions for the inventory analysis of this configuration are:

- The additional amount of ONP and GGS required is transported from the same locations as the base case mill. A credit for recycling this amount of wastepaper was included, which otherwise would be landfilled.
- The DIP sludge can be dewatered and burned in the boiler house.
- The additional energy required in the boiler house to produce steam is supplied by natural gas.

As a consequence of the last assumption, Table 3 shows that natural gas consumption increases by approximately 40%, and the amount of sludge used as an energy source is twice as high as in the baseline model.

In the 100% CE configuration, all the electricity consumed by the mill is co-generated on site. The required amount of boiler steam for this configuration is around twice as much as for the baseline model, and therefore the total amount of energy required at the mill also increases (see Table 3). It was assumed that this additional steam could not be produced entirely from biomass due to hog fuel availability. Hog fuel consumption was doubled, and the balance of the fuel requirements was covered by natural gas. As a result, natural gas consumption for this configuration is around 4 times more than that for the baseline model. The last configuration is a combination of the first two models. As a consequence, the total energy requirements increase by approximately 30%, and the natural gas consumption for this configuration is nearly twice as much as that for the baseline model.

Figure 11 shows a comparison of the Global Warming Potential (GWP) for the baseline model and the energy-oriented scenarios. All the configurations result in improvements in GWP, with reductions from 20 to 40%, despite the fact that the overall energy consumption increases for the three scenarios. This result can be explained by the energy source: electricity sourced in good part from coal (33%) has been replaced with electricity generated from natural gas and biomass (which has been assumed CO_2 neutral). There is an increase in the contribution from chemical production when more DIP is produced. Contributions from landfill and transportation remain almost constant for the three alternative scenarios.

The alternative mill configurations point to strategies that would improve the environmental performance from the impact categories considered (Figure 10). However, for the impact categories that are more sensitive to natural gas consumption (i.e., acidification, photochemical smog, and human health particles), the category indicator results increase as a consequence of the rise in natural gas consumption. For instance, Figure 12 shows that despite the fact that the contribution from electricity production is reduced or eliminated, the contributions from biomass and natural gas combustion, and especially from natural gas production, increase significantly, resulting in a net increase in the photochemical smog indicator.

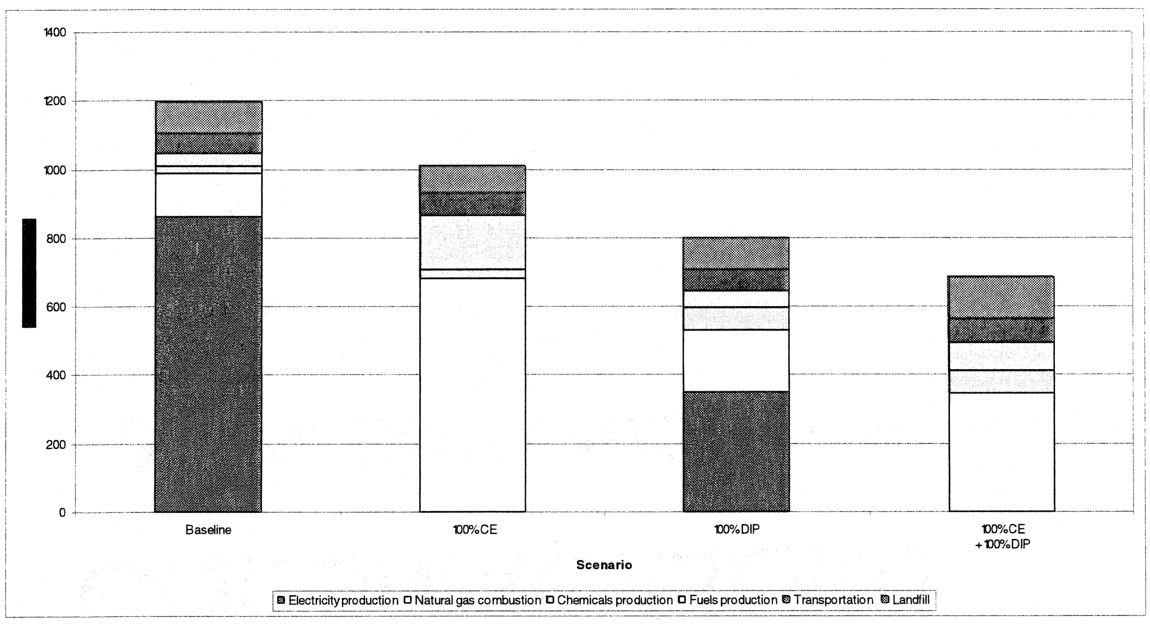

Figure 11: GWP of alternative mill configurations

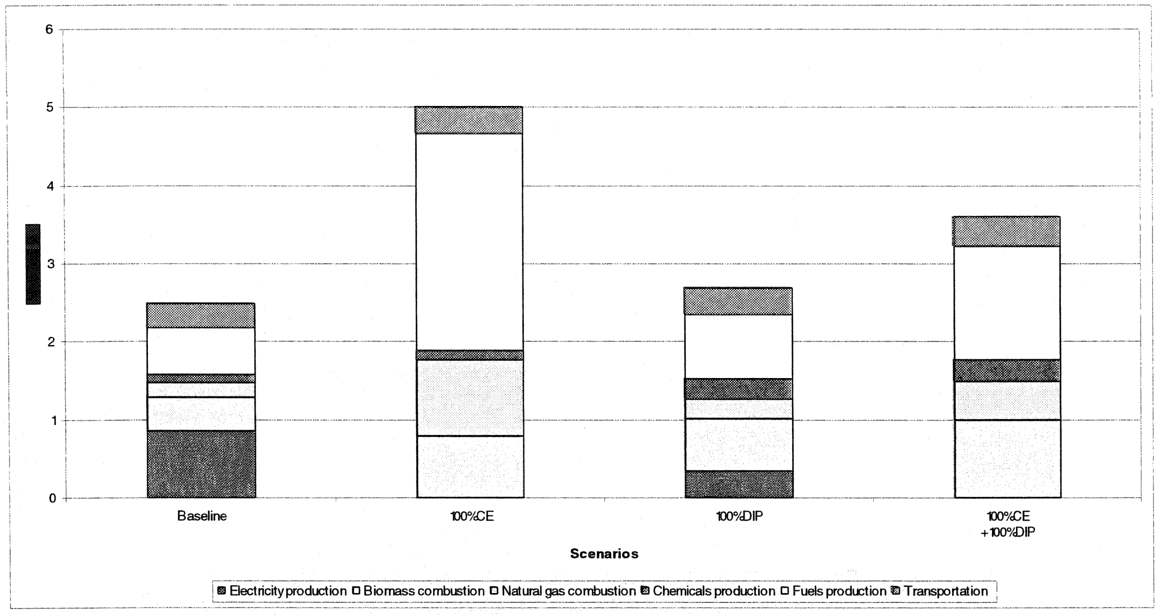

Figure 12: Photochemical smog potential of alternative mill configurations

Impact of Mill Location

Since these scenarios are mainly oriented towards reducing the purchased electricity consumption, the environmental benefits from modifying the mill depend strongly on the at-source power mix, and therefore on the mill location. In order to understand better the significance of this non-process parameter, the average power mix for three different Canadian provinces was considered: Ontario, Quebec, and Alberta. Table 4 presents the power mix for each province as well as the corresponding GWP.

Table 4: Power mixes and GWP for three Canadian provinces

Province	Fossil (%)	Nuclear (%)	Hydro (%)	GWP (gCO_2/MWh)
Alberta	91	0	9	8.59e+5
Ontario	33	39	28	3.87e+5
Quebec	1	4	95	1.85e+4

The electricity production in the baseline LCA was substituted by these three different models and the GWP of the entire system (i.e., per 1 admt) was re-calculated. The results are shown in Figure 13. It can be observed that the mill location dramatically influences the category indicator results, and consequently, the sensitivity and scenario analysis results.

Note that the GWP was calculated using secondary inventory data (sourced on FRANKLIN database) for comparative purposes and it does not represent real emissions (e.g., the model for hydropower considers zero emissions). Also, note that the result for Ontario does not represent the same baseline model result, since in this latter site specific data was used.

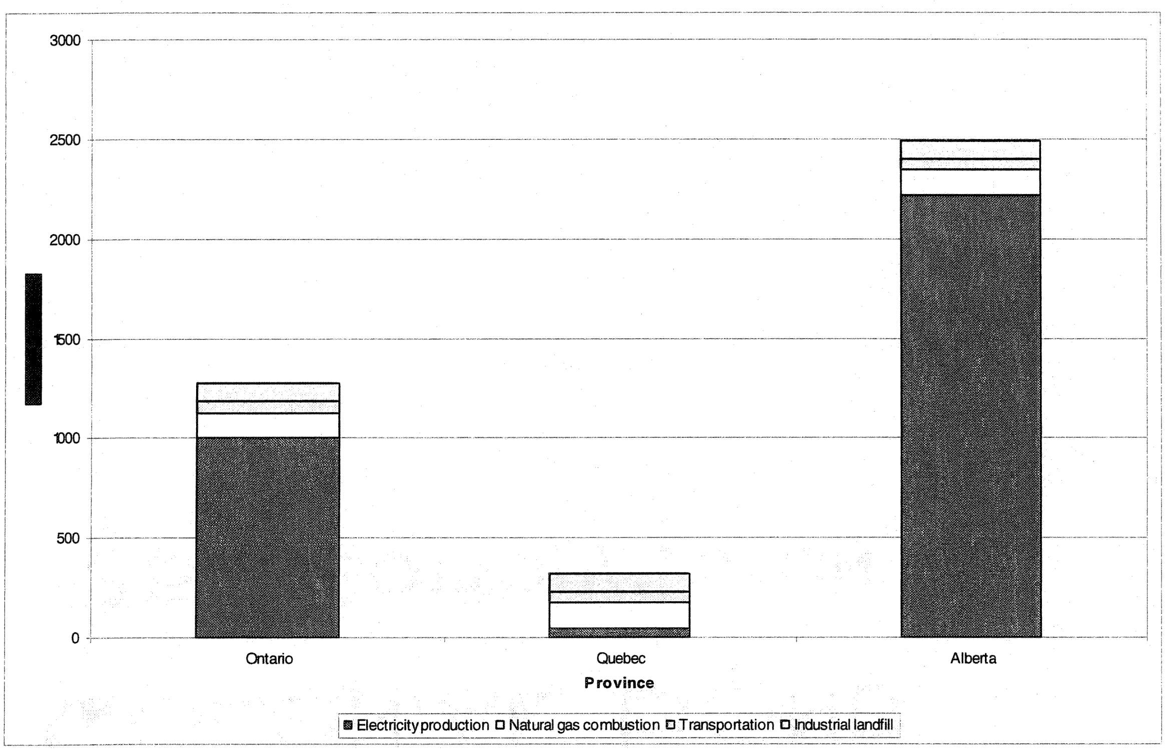

Figure 13: GWP per 1 admt of newsprint for three different mill locations

Effluent Reduction Scenarios

3 scenarios were developed whose goal was to reduce nutrient emissions from the newsprint mill, as follows:

- Tertiary treatment of the current quantity of effluent by alum-polymer coagulation/flocculation,
- Implementation of water conservation programs in order to reduce the volume of effluent by in-mill process modifications, and tertiary treatment of the reduced amount of effluent by coagulation/flocculation, and
- Implementation of a membrane filtration technology after secondary treatment in order to reuse the effluent as fresh water in the process.

The two first scenarios are based on data from a tertiary treatment plant in a TMP-DIP newsprint mill in Sweden utilizing dissolved air flotation aided by chemical coagulation and flocculation with alum and polymer, in order to reduce COD and phosphorous discharges (Thoren et al. 1997). This process produces a quantity of sludge that is difficult to dewater and must be landfilled (European Commission 2001). The amount of sludge generated for these scenarios was not addressed because reliable data was not available. Table 5 presents the main characteristics of the two first scenarios in terms of quantity and quality of the discharged effluents.

Table 5: Effluent characteristics for tertiary treatment scenarios

Parameter	Units	Baseline	TT	WC+TT
Flow	m^3/admt	45.4	45.4	25.0
BOD	kg/admt	0.4	0.2	0.16
PO_4-P	g/admt	65	4.0	2.8
N-t	g/admt	183	100	60

Note: TT: Current amount of effluent receives tertiary treatment (TT)

WC+TT: Water conservation (WC) programs are applied and the consequent reduced amount of effluents receives tertiary treatment (TT).

For achieving the zero effluent treatment scenario, an approach based on membrane technology was assumed. Depending on the applicable membrane cut-off size and the filtering pressure, it is possible to remove essentially 100% of the colloidal and suspended organic material with ultrafiltration, producing a filtrate with sufficient quality to replace most of the fresh water used in the process. The sludge generated can be sent to biological treatment or may require further concentration into a solid fuel for disposal by incineration (IPPC 2001). The small amount of sludge generated for this scenario has also not been quantified. Figure 14 shows the comparative results for the eutrophication impact category, which is sensitive to the nutrient emissions from the newsprint mill.

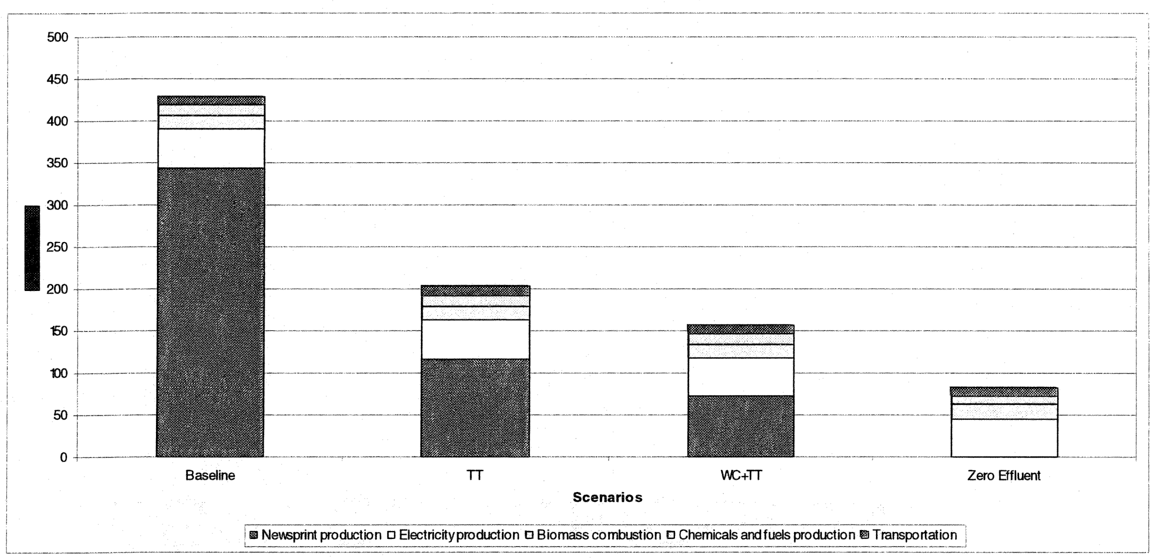

Figure 14: Eutrophication potential for alternative effluent scenarios

The contribution from the newsprint mill effluent represents around 80% of the eutrophication potential in the baseline model. With the implementation of tertiary treatment, the eutrophication potential can decrease by 50 to 60% and with the zero effluent treatment technology, by 80% through the elimination of the newsprint mill contribution.

Additional Scenario Regarding Waste Paper Management Options

An additional scenario analysis was completed in order to analyze the alternatives of recycling wastepaper for DIP production, or incinerating it in a city cogeneration plant to recover electricity. There is a concern associated with this question due to the impact from wastepaper transportation. In order to assess this question, the baseline model system was expanded to include the wastepaper transportation from curbsides to material recovery facilities. The results show that the contribution due to this activity in all impact categories is negligible (<<1%) for the base case mill. The scenarios described in Table 6 were compared.

Table 6: Characteristics of Additional Scenarios

Parameter	**Units**	**Baseline**	**100% DIP**	**55% EW**
DIP content	%	20	100	20
Electricity Breakdown:				
Purchased from the grid	%	98	98	45
Co-generated	%	2	2	55

For the 55% electricity from wastepaper (EW) scenario, the additional amount of wastepaper that was recycled in the 100% DIP scenario was incinerated in the urban centre, generating electricity for the grid. The amount of electricity produced in this way constituted 55% the total electricity consumption at the mill. Since these alternatives are oriented towards reducing the impacts caused by energy consumption, the model was also run for the three power mixes which were presented in Table 4. Figures 15, 16, and 17 present the profiles normalized against the baseline model results. Scores lower than 1 represent a decrease in the category indicator results, and therefore an improvement in the environmental performance.

The results show that when fossil fuel sources have a high contribution in the electricity mix (e.g., Ontario and Alberta) that there are greater environmental benefits. The 55% EW scenario has benefits mainly for global impacts as well as for eco-toxicity and human toxicity, presenting a range of improvement from 7% to 30%. For the power mixes where both alternatives have environmental benefits, the difference in environmental performance improvement is less than 10% for most of the impact categories, except for regional impacts, for which 100% DIP represents a better alternative (since the 55% EW scenario produces a higher quantity of combustion gases, which contribute to regional impacts), and for ozone depletion for which 55% EW is a better alternative (since the chemical consumption is higher for the 100% DIP scenario).

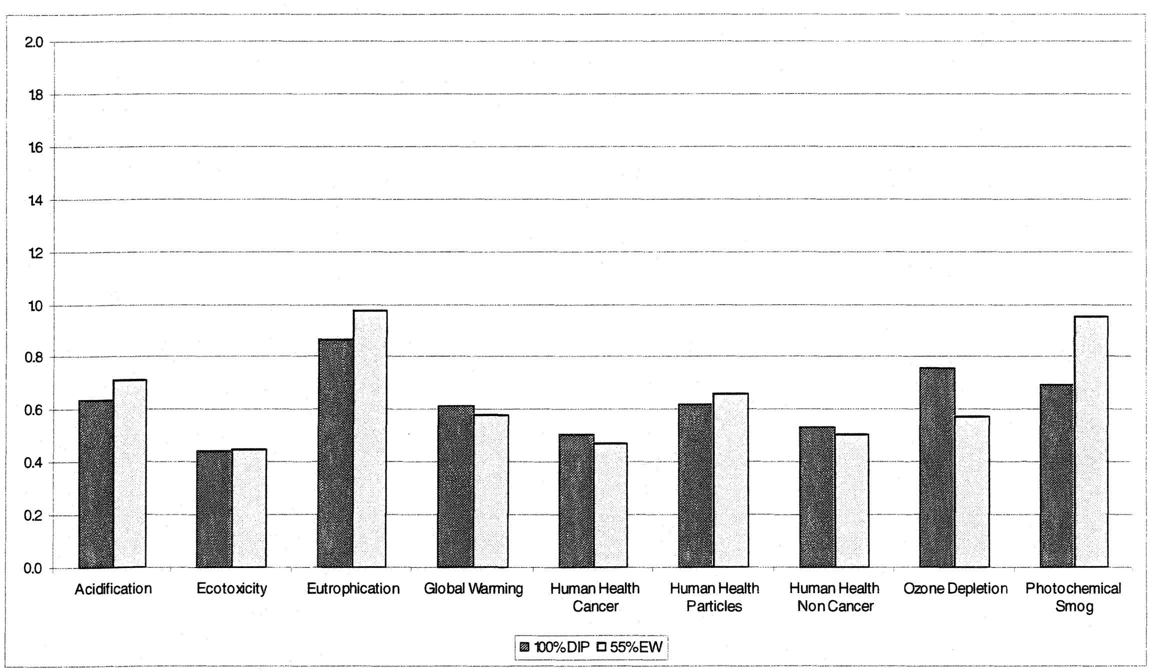

Figure 15: Normalized results for additional scenario- Ontario power mix

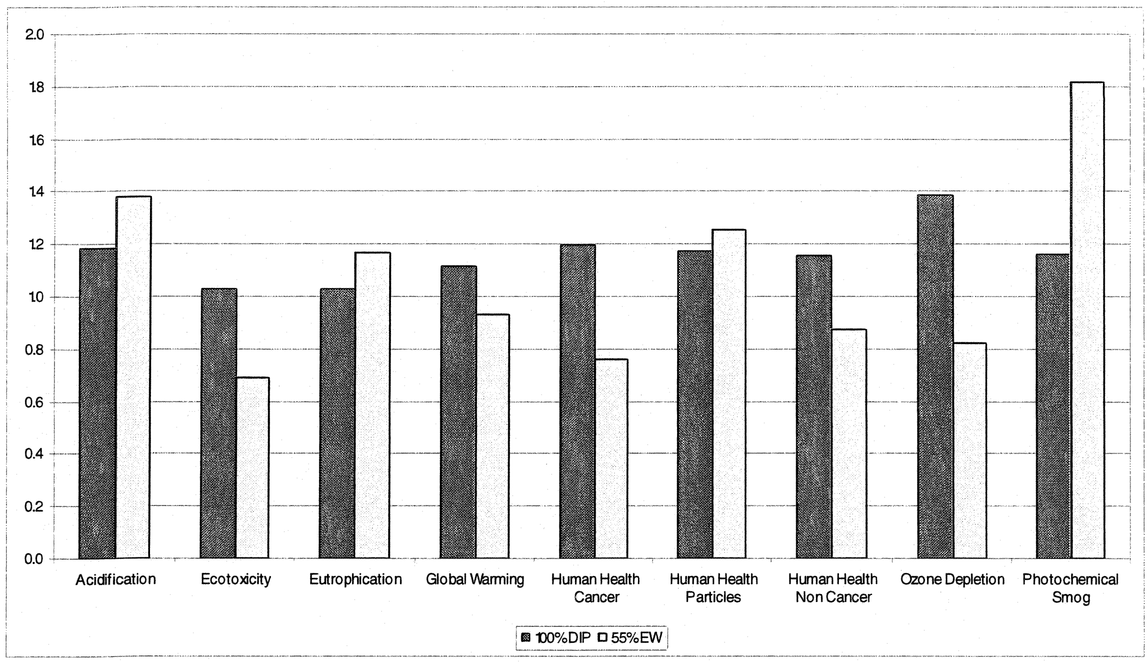

Figure 16: Normalized results for additional scenario - Quebec power mix

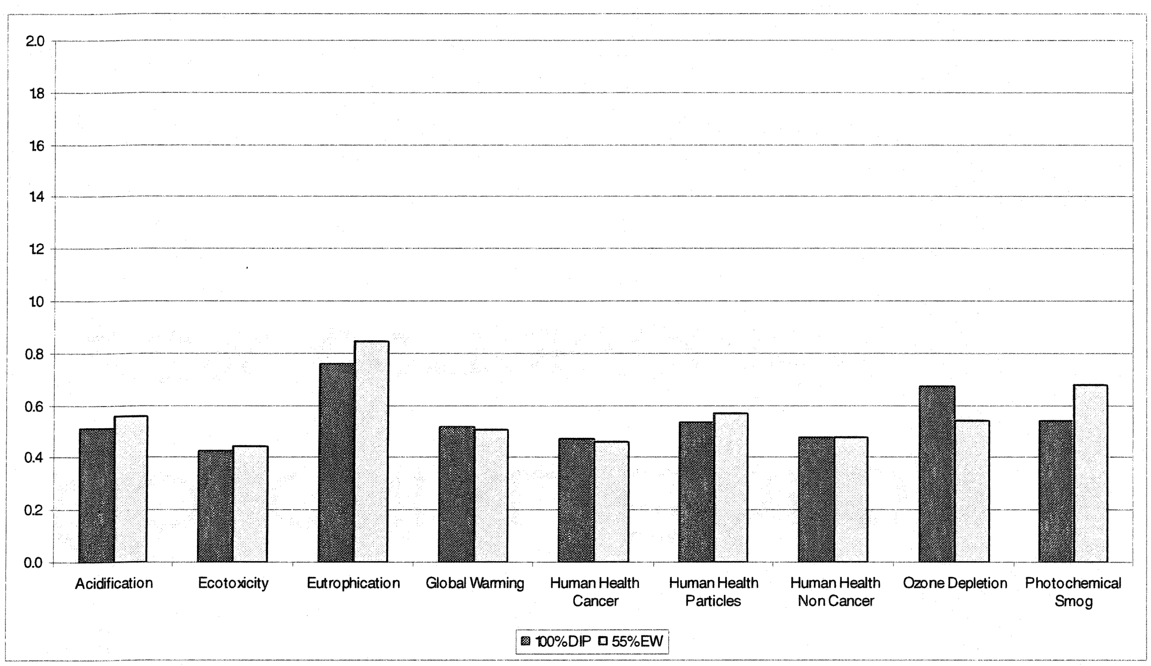

Figure 17: Normalized results for additional scenario- Alberta power mix

Conclusions

A cradle-to-gate LCA study for the production of 1 admt of newsprint was completed following ISO 14040 standards. The following general conclusions were drawn from this study:

- A sensitivity analysis of the baseline model results shows that energy consumption, mainly in the form of electricity and natural gas to produce steam, and effluent emissions are the process parameters that show significant sensitivity (>10%) in the category indicator results.
- The electricity mix, which varies with mill location, is a non-process parameter that dramatically affects baseline model results and the potential benefits of the energy management scenarios.
- The developed alternative mill configurations involving increased production of DIP and/or co-generation systems have potentially important environmental benefits for the system studied (e.g., 20-40% reduction in Global Warming Potential), except for the impact categories that are more sensitive to natural gas consumption (i.e., acidification, photochemical smog, and human health particles).
- The effluent-oriented scenarios show a significant reduction in eutrophication potential (50-80%), with higher benefits from the membrane technology, which completely eliminates the contribution from newsprint mill effluents to eutrophication, optimizes water resource use, and has available alternatives to sludge landfilling.
- When fossil fuel sources have a high contribution in the electricity mix, recycling wastepaper for DIP production, or incinerating it in a city cogeneration plant to recover electricity have similar potential benefits.

This work comprises the first results of an overall program themed "Life Cycle Thinking in the Pulp and Paper Industry", which is oriented towards developing the LCA application as an engineering tool in the assessment of process variants.

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APPENDIX C: MODELING OF THE SYSTEM STUDIED

This appendix presents details about the unit processes modeling. The most important unit processes are illustrated through flow charts containing the main activities, including transportation which is represented by dashed lines. Details on data sources as well on the calculation procedures are also provided. At the end of the model description is presented a mass balance on wood and water, when applicable.

The following are special units used in pulp and paper industry:

MBF = Thousand board feed (equivalent to 1.37 ton)
bdmt = bone dried metric ton (moisture content = 0%)
admt = air dried metric ton (moisture content = 10%)

FORESTRY

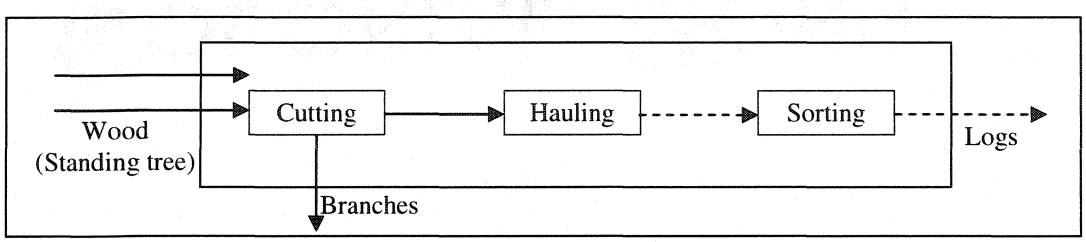

Figure C.1: Flowchart of forestry operations

Table C.1: Description of forestry model

Unit process name: Forestry							
Unit process description: Harvesting operations							
Reference flow: 1 m3 of wood logs							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Resources							
Wood	bdmt	**0,43**	Woodlands	Primary/secondary	10% tree are branches left in the woodlands Reference: IVAM	(0,32+0,07)[bdmt logs]/0,9[bdmt logs/bdmt wood]	Branches are not included in the inventory because they are left in the woods
Land use	m2yr	13559,32	Woodlands	Primary	From primary sources: Yield = 59m3/ha; and relaxation period = 80 yrs	1[m3]/59[m3/ha]*10000[m2/ha]*80yr	
Materials/fuels							
Trailer diesel	L	2,34	Logs transportation and woodlands operations	Primary	- Logs transportation and harvesting operations can be represented by the same model. - Amount is calculated by dividing yearly fuel consumption between yearly woodlands production	2707843[L]/1158777[m3]	Fuel consumption corresponding to round trips for logs transportation
Truck (single) gasoline	L	0,15	Personnel transportation	Primary	Amount is calculated by dividing yearly fuel consumption between yearly woodlands production	168180[L]/1158777[m3]	
Aviation turbo	L	0,03	idem	Primary	idem	32162[L]/1158777[m3]	
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Product							
Spruce logs	bdmt	**0,32**	On-site sawmill	Primary/secondary	From primary sources: production in vol. = 75,4% spruce and 24,6% aspen Basic density of black spruce: 0,423 bdmt/m3 (Reference: Paper Making Science and Technology. Helsinki University of Technology. Finland, 1998)	0,754[m3]x0,423[bdmt/m3]	
Coproducts							
Aspen logs	bdmt	**0,07**	Plywood mills (out of the system)	Primary/secondary	Basic density of trembling aspen: 0,286 bdmt/m3 Reference: idem	0,246[m3]x0,286[bdmt/m3]	
Mass balance on wood: Wood = wood (spruce) + wood (aspen) + wood (branches): 0,43[bdmt] = (0,32+0,07+0,04)[bdmt]							

SAWMILL

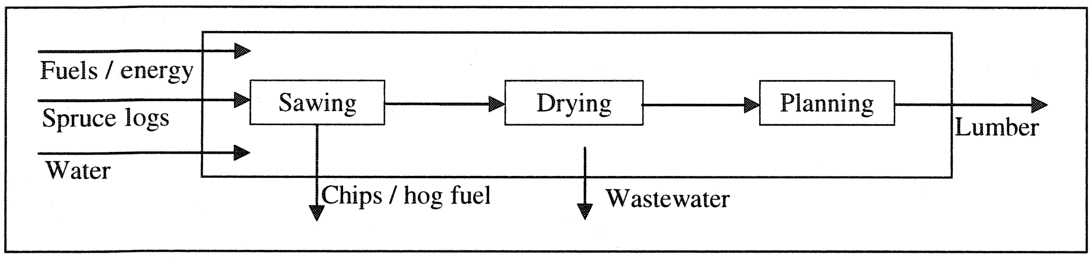

Figure C.2: Flowchart of sawmill operations

Table C.2: Description of sawmill model

Unit process name: Sawmill							
Unit process description: Sawmill operations to produce lumber for construction industry as main product. Data referred to FY2001 production: 98461 MBF							
Reference flow: 1 MBF of lumber							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Resources							
Water	ton	*1,44*	River	Primary	From primary sources: Fresh water = 100 gpm. Assumption of 260 d/yr (Monday to Friday)	100 [gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/98461[MBF/yr]x260[d/yr]	
Materials/fuels							
Spruce logs	bdmt	**3,49**	Forestry	Primary	From mass balance around the sawmill. Assuming negligible consistency of the effluent.	(1.37+1.57+0.55) [bdmt]	
Trailer diesel	L	5.33	Mobile equipments	Primary	- Mobile equipements for sawmill operations can be represented by trailer diesel model. - Amount is calculated by dividing yearly fuel consumption between yearly lumber production	524427[L]/98461[MBF]	
Truck (single) gasoline	L	0.44	Personnel transp.	Primary	Amount is calculated by dividing yearly fuel consumption between yearly lumber production	43273[L]/98461[MBF]	
Aviation turbo	mL	1.49	idem	Primary	idem	147[L]/98461[MBF]	
Electricity/heat							
Electricity	MWh	0.16		Primary	Amount is calculated by dividing yearly energy consumption between yearly lumber production	15638[MWh]/98461[MBF]	
Steam	10^6BTU	1.07	Boiler house	Primary	idem	105714[10^6BTU]/98461[MBF]	
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Product							
Lumber	bdmt	**1,37**	Construction industry (out of the system)	Secondary	Assuming 1.37 bdmt/MBF Reference: US Department of Agriculture - Foreign Agricutural Service - Forest Products Shipping Weights and Volumes	1.37[bdmt/MBF]x1[MBF]	
Coproducts							
Chips	bdmt	**1,57**	Thermo-mechanical pulping (TMP)	Primary	Amount is calculated by dividing yearly co-product production between yearly lumber production	154929[bdmt]/98461[MBF]	
Hog fuel	bdmt	**0,55**	Boiler house	Primary	idem	54191[bdmt]/98461[MBF]	It does not have economical value
Waste to treatment							
Wastewater	ton	*4,32*	Effluent treatment plant	Primary	From primary sources: Wastewater = 300 gpm. Assumption of 260 d/yr (Monday to Friday)	300 [gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/98461[MBF/yr]x260[d/yr]	There is an internal water input of 200 gpm from TMP, not included in the inventory
Mass balance on wood: Spruce logs = lumber + chips + hog fuel: 3,49[bdmt] = (1,37+1,57+0,55)[bdmt]							
Mass balance on water: Fresh water + internal inputs = wastewater: (100+200)[gpm]=300[gpm]							

THERMOMECANICAL PULPING (TMP)

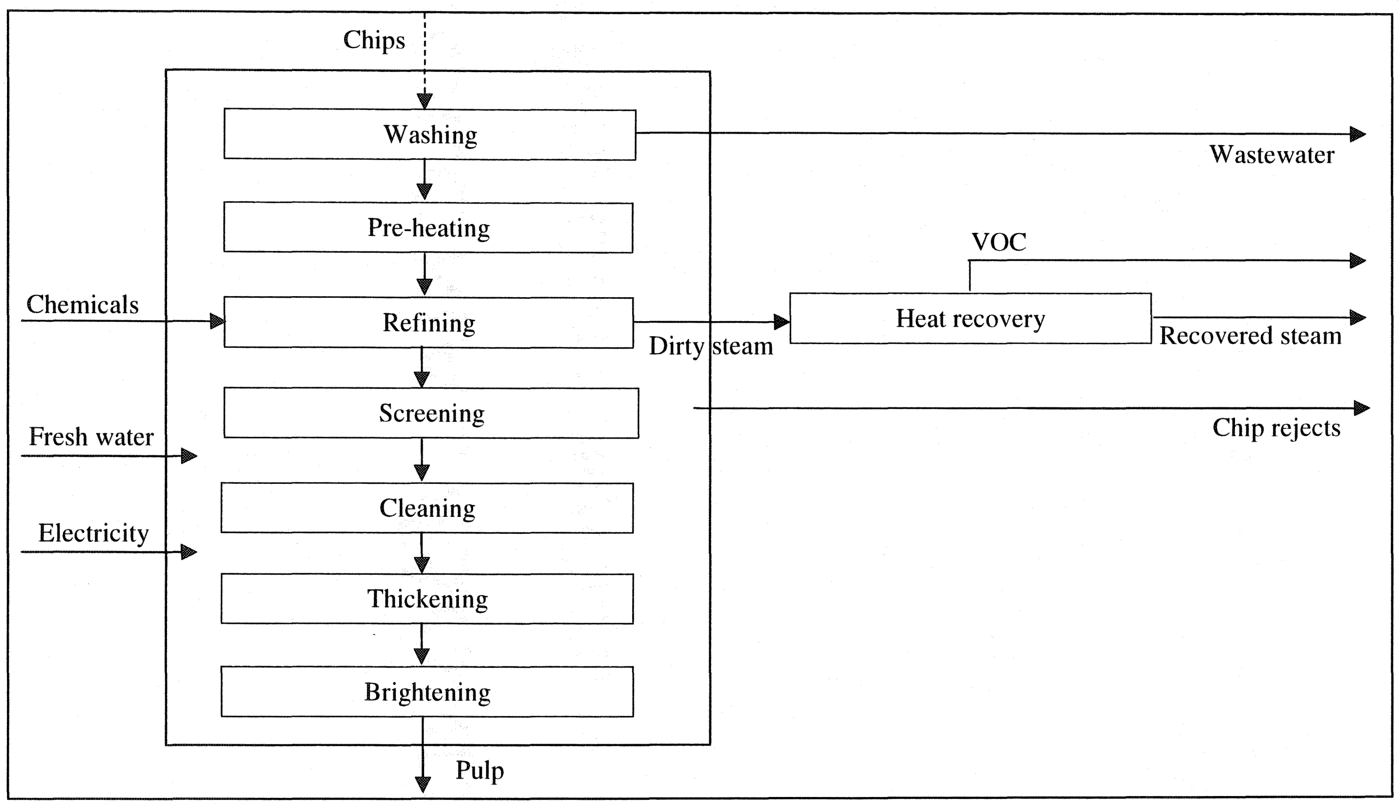

Figure C.3: Flowchart of thermomecanical pulping

Table C.3: Description of thermomechanical pulping model

Inputs	Unit	Amount	Origin	Data source	Calculation data / Assumptions	Calculations	Notes
Unit process name: Thermomechanical pulping (TMP)							
Unit process description: Chips are reduced to a fibrous mass (i.e. pulp) by a mechanical separation of the fibers with the application of heat and pressure							
Reference flow: 1 bdmt of TMP pulp							
Resources							
Water	ton	*12,70*	River	Primary	From primary sources: Fresh water = 2050 gpm to produce 879,7 bdmt/day.	2050 [gal/min]x3,785[L/gal]x1440[min/d] /1000[L/ton]/879,7[bdmt/d]	
Materials/fuels							
Chips	bdmt	**1,07**	Sawmill	Primary	Amount is calculated by dividing yearly chips consumption between yearly pulp production	332959[bdmt]/312059[bdmt]	Includes chips produce on-site and off-site
Sulphur dioxide	kg	5,53	Suppliers	Primary	Amount is calculated by dividing yearly chemical consumption between yearly pulp production	1725657[kg]/312059[bdmt]	
NaOH	kg	3,55	Suppliers	Primary	idem	1106960[kg]/312059[bdmt]	
Borol	kg	3,08	Suppliers	Primary	idem	960406[kg]/312059[bdmt]	
DTPA	kg	1,11	Suppliers	Primary	idem	345809[kg]/312059[bdmt]	Refer to "chemicals organic ETH T" model.
Trailer diesel	L	0,84	Chips transportation	Primary / Secondary	One way transportation. Fuel consumption calculated by multiplying total loads by average distance and considering a fuel efficiency of 2,55[km/L] (Ref. EPDS guidelines, 97)	9308[loads]x72,1[km]/2,55[km/L] /312059[bdmt]	Includes transportation for the off-site produced chips.
Electricity/heat							
Electricity	MWh	2,54		Primary	Amount is calculated by dividing yearly electricity consumption between yearly pulp production	791767[MWh]/312059[bdmt]	
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Product							
TMP pulp	bdmt	**1,00**	Paper machines				Reference flow
Coproducts							
Recovered steam	10^6BTU	2,02	Paper machines	Primary	Amount is calculated by dividing yearly net steam distribution between yearly pulp production	629173[10^6BTU]/312059[bdmt]	No burdens allocated to this output
Chip rejects	bdmt	**0,04**	Boiler house	Primary	From mass balance around TMP. See equation below	1,07[bdmt]-1,00[bdmt]-0,0016[bdmt/tonH2O]x11,09[tonH2O]	idem
Emissions to air							
VOC	kg	0,11	Atmosphere	Primary	Amount is calculated by dividing yearly VOC emission between yearly pulp production (FY-00)	35600[kg]/318181[bdmt]	From heat recovery unit (HRU)
Waste to treatment							
Wastewater	ton	*11,09*	Effluent treatment plant	Primary	From primary sources: Wastewater = 1790 gpm (0,3% consistency) to produce 879,7 bdmt/day.	1790 [gal/min]x3,785[L/gal]x1440[min/d] /1000[L/ton]/879,7[bdmt/d]	There are internal water input and outputs not included in the inventory (see balance below)
Mass balance on wood: Chips = pulp + chips rejects + fibre in wastewater: 1,07[bdmt] = (1,00+0,04)[bdmt]+0,003[bdmt/tonH2O]x11,09[tonH2O]							
Mass balance on water: Fresh water + internal inputs = wastewater + internal outputs: (2050+2385)[gpm] = (1790+2617)[gpm]. Note: 0,6% error							

DEINK PULPING (DIP)

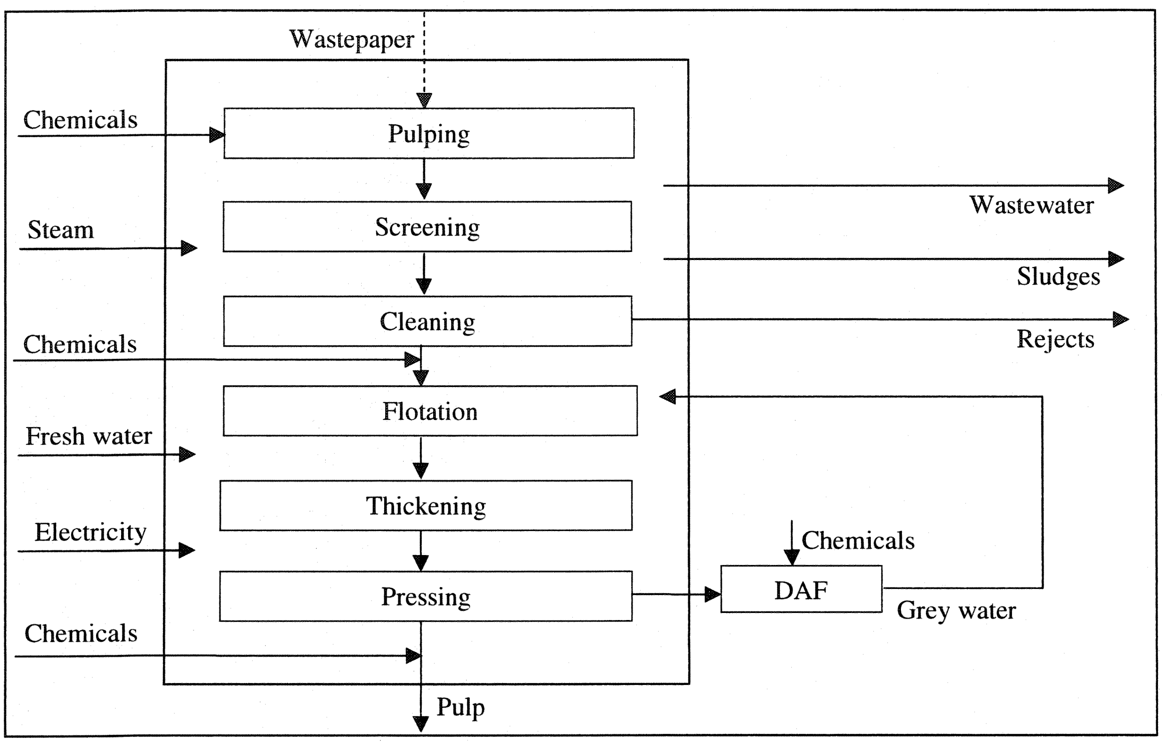

Figure C.4: Flowchart of deink pulping

Table C.4: Description of deink pulping model

Unit process name: Deink pulping (DIP)

Unit process description: Repulping of wastepaper and removal of the ink from the obtained fibers

Reference flow: 1 bdmt of DIP pulp

Inputs	Unit	Amount	Origin	Data source	Calculation data / Assumptions	Calculations	Notes
Resources							
Wastepaper	bdmt	**1,17**	Suppliers	Primary	Amount is calculated by dividing yearly wastepaper consumption between yearly pulp production	64935[bdmt]/55325[bdmt]	
Water	ton	*4,04*	River	Primary	From primary sources: Fresh water = 101 gpm to produce 136.2 bdmt/day.	101 [gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/136.2[bdmt/d]	
Materials/fuels							
Sodium silicate	kg	17.55	Suppliers	Primary	Measured		
NaOH	kg	9.94	Suppliers	Primary	idem		
Sulphur dioxide	kg	13.00	Suppliers	Primary	idem		
H2O2	kg	10.53	Suppliers	Primary	idem		
Soap	kg	6.43	Suppliers	Primary	idem		Refer to "stearic acid" model.
CaCl2	kg	8.19	Suppliers	Primary	idem		Refer to "chemicals inorganic ETH T" model.
Coagulant/flocculant	kg	1.30	Suppliers	Primary	idem		Refer to "chemicals organic ETH T" model.
Biocide	kg	0.10	Suppliers	Primary	idem		idem
Trailer diesel	L	1.85	Wastepaper transportation	Primary	One way transportation. Fuel consumption calculated by multiplying total ton by average distance and considering a fuel efficiency of 0.023[L/ton-km] (Ref. EPDS guidelines, 97)	9594.21[ton]x466.967[km] x0.023[L/ton-km]/55325[bdmt]	
Locomotive diesel	L	7.18	idem	Primary	idem. Fuel efficiency: 0.007[L/ton-km]	61501[ton]x987.08[km] x0.007[L/ton-km]/55325[bdmt]	
Electricity/heat							
Electricity	MWh	0.45		Primary	Amount is calculated by dividing yearly energy consumption between yearly pulp production	24977[MWh]/55325[bdmt]	
Steam	10^6BTU	1.25	Boiler house	Primary	idem	69145[10^6BTU]/55325[bdmt]	
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Product							
DIP pulp	bdmt	**1,00**	Paper machines				Reference flow
Waste to treatment							
Wastewater	ton	*33,85*	Effluent treatment plant	Primary	From primary sources: Wastewater = 846 gpm (~0% consistency) to produce 136.2 bdmt/day.	846[gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/136.2[bdmt/d]	There are internal water input and outputs not included in the inventory (see balance below)
Sludge	bdmt	**0,14**	Sludge treatment	Primary	Amount is calculated by dividing yearly waste generation between yearly pulp production	7940[bdmt]/55325[bdmt]	
Rejects	ton	**0,03**	Industrial landfill	Primary	idem. Solids with 80% average moisture content	304[bdmt]/0.2[bdmt/ton]/55325[bdmt]	

Mass balance on wood: Wastepaper = pulp + sludge + process wastes: 1.17[bdmt] = (1.00+0.14)[bdmt]+0.03[ton]x0.2[bdmt/ton]. Note: 2% error

Mass balance on water: Fresh water + internal inputs = wastewater + internal outputs: (101+1805)[gpm] = (846+1060)[gpm]

PAPER MAKING

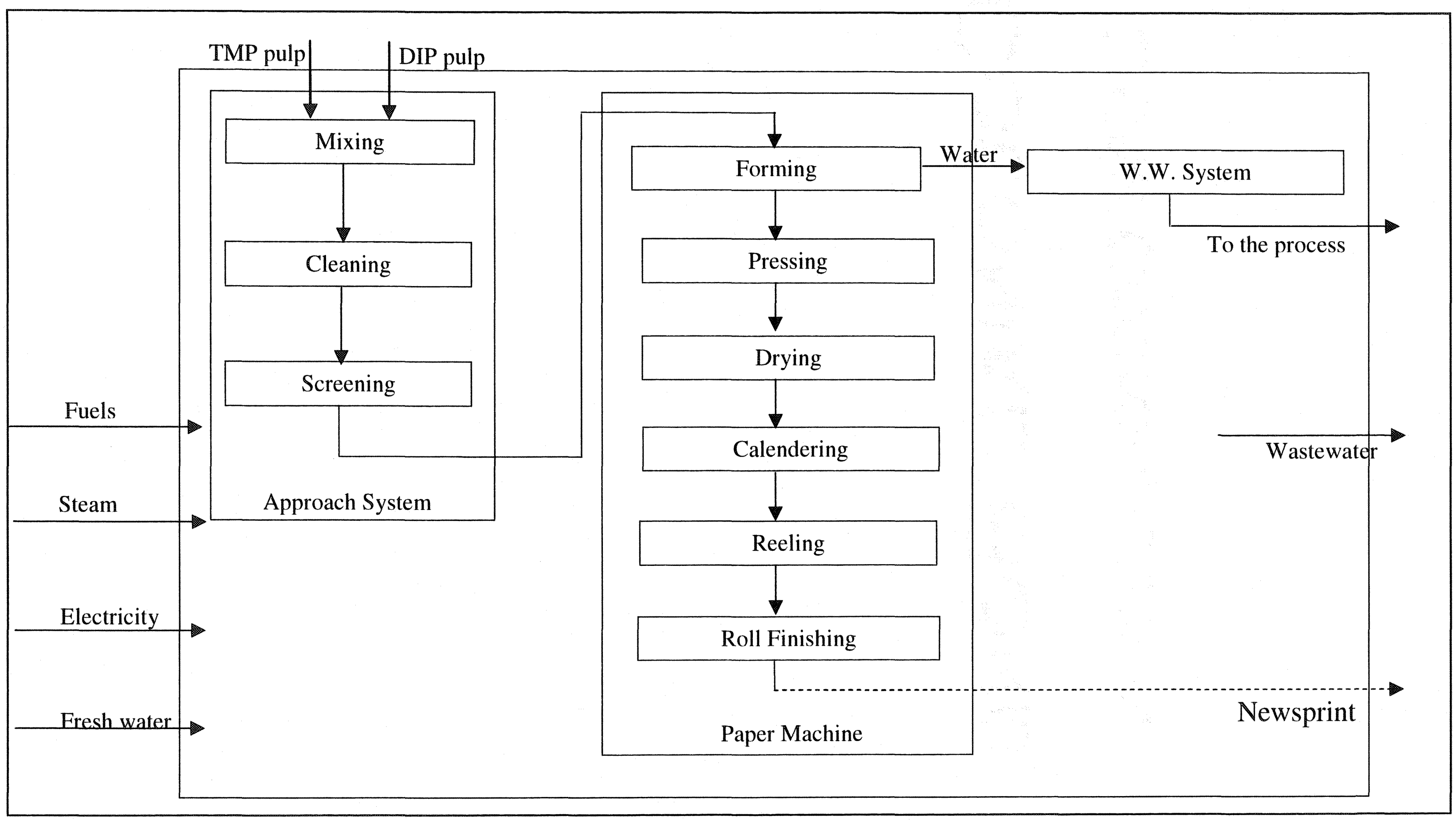

Figure C.5: Flowchart of paper making

Table C.5: Description of paper making model

Unit process name: Paper making

Unit process description: Extraction of water from the pulp and formation of a paper sheet with defined properties

Reference flow: 1 admt of newsprint

Inputs	Unit	Amount	Origin	Data source	Calculation data / Assumptions	Calculations	Notes
Resources							
Water	ton	*28,07*	River	Primary	From primary sources: Fresh water = 6347 gpm to produce 1232.22 admt/day.	6347[gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/1232.22[admt/d]	Water for process
Water	ton	2.59	River	Primary	From primary sources: Fresh water = 586 gpm when producing 1232.22 admt/day.	586[gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/1232.22[admt/d]	Water for general uses (e.g. bathrooms)
Materials/fuels							
TMP pulp	bdmt	**0,74**	Thermomechanical pulping	Primary	Amount is calculated by dividing yearly pulp consumption to produce newsprint between yearly newsprint production	312059[bdmt]x0.779/328226[admt]	77.9% of the TMP production is used for newsprint production. the remaining is used for UCGS prod.
DIP pulp	bdmt	**0,17**	Deink pulping	Primary	idem	55325[bdmt]/328226[admt]	
Trailer diesel	L	0.87	Mobile equipements	Primary	- Mobile equipements for newsprint mill operations can be represented by trailer diesel model. - Amount is calculated by dividing yearly fuel consumption between yearly newsprint production	286125[L]/328226[admt]	
Propane vehicles	L	0.64	Fork lift trucks	Primary	Amount is calculated by dividing yearly fuel consumption between yearly newsprint production	211531[L]/328226[admt]	
Truck (single) gasoline	L	0.12	Personnel transportation	Primary	idem	39100[L]/328226[admt]	
Aviation turbo	L	0.10	idem	Primary	idem	33976[L]/328226[admt]	
Locomotive diesel	tkm	669.00	Newsprint distribution	Primary	Amount calculated with traffic information	0.75[admt]x892[km]	
Trailer diesel	tkm	262.00	idem	Primary	idem	0.25[admt]x1048[km]	
Electricity/heat							
Electricity	MWh	0.56		Primary	Amount is calculated by dividing yearly energy consumption between yearly newsprint production	226934[MWh]x0.812/328226[admt]	81.2% represents newsprint production (the remaining corresponds to UCGS). Includes energy for general uses and mill losses
Steam	10^6BTU	5.29	Boiler house	Primary	idem	2137130[10^6BTU]x0.812/328226[admt]	idem
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Product							
Newsprint	admt	**1,00**	Printing facilities				Reference flow
Waste to treatment							
Wastewater	ton	*27,23*	Effluent treatment plant	Primary	From primary sources: Wastewater = 6155 gpm (~0% consistency) to produce 1232.22 admt/day.	6155 [gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/1232.22[admt/d]	Process wastewater. There are internal water input and outputs not included in the inventory (see balance below)
Wastewater	ton	1.19	Effluent treatment plant	Primary	From primary sources: Wastewater = 270 gpm when producing 1232.22 admt/day.	270[gal/min]x3.785[L/gal]x1440[min/d] /1000[L/ton]/1232.22[admt/d]	General uses wastewater
Solid wastes	kg	3.76	Industrial landfill	Primary	Amount is calculated by dividing yearly waste generation between yearly newsprint production	1519[ton]*0.812/328226[admt] /1000[kg/ton]	81.2% represents newsprint production (the remaining corresponds to UCGS)

Mass balance on wood: Newsprint = TMP pulp + DIP pulp : 0.9[bdmt] = (0.74+0.17)[bdmt]. Note: 1% error

Mass balance on water: Fresh water + internal inputs = wastewater + internal outputs: (6347+6102)[gpm] = (6155+6294)[gpm]

EFFLUENT TREATMENT PLANT (ETP)

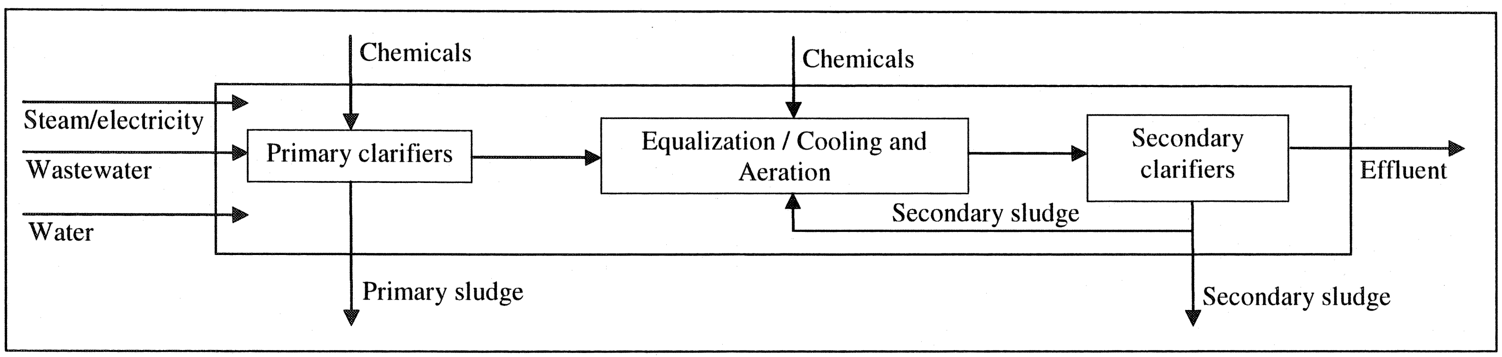

Figure C.6: Flowchart of the effluent treatment plant

Table C.6: Description of effluent treatment model

Inputs	Unit	Amount	Origin	Data source	Calculation data / Assumptions	Calculations	Notes
Unit process name: Effluent treatment							
Unit process description: Gravity separation and biological treatment of newsprint mill effluents							
Reference flow: 1 ton of wastewater (1 m3)							
Waste treatment							
Wastewater	ton	1,00	Newsprint mill				Reference flow
Resources							
Water	ton	0,04	River	Primary	From primary sources: Fresh water = 400 gpm to treat 50068 m3/day.	400[gal/min]x3,785[L/gal]x1440[min/d] /1000[L/ton]/50068[m3/d]	
Materials/fuels							
Ammonia	g	29,30	Suppliers	Primary	Measured		
H2O2	g	9,00	Suppliers	Primary	idem		
Phosphoric acid	g	24,10	Suppliers	Primary	idem		
Lime	g	2,50	Suppliers	Primary	idem		
Electricity/heat							
Electricity	kWh	1,24		Primary	Amount is calculated by dividing yearly energy consumption between yearly m3 of effluent treated (2001)	22552000[kWh]/18206305[m3]	
Steam	10^3BTU	2,44	Boiler house	Primary	idem	44408000[10^3BTU]/18206305[m3]	
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Emissions to air							
Ammonia	g	0,01	Atmosphere	Primary	Amount is calculated by dividing yearly emission between yearly m3 of effluent treated (2002)	225e3[g]/17252405[m3]	Fugitive releases
Emissions to water							
COD	kg	0,16	River	Primary	Amount is calculated by dividing daily emission between daily m3 of effluent treated	8000[kg]/50068[m3]	Set to zero in LCA software to avoid double counting with BOD
BOD	g	8,47	River	Primary	idem	424000[g]/50068[m3]	
TSS	g	29,22	River	Primary	idem	1463e3[g]/50068[m3]	
Kjeldahl-N	g	3,17	River	Primary	idem	158800[g]/50068[m3]	
NH3 (as N)	g	0,49	River	Primary	idem	24400[g]/50068[m3]	
Nitrate	g	0,27	River	Primary	idem	13400[g]/50068[m3]	
Nitrite	g	0,10	River	Primary	idem	5200[g]/50068[m3]	
Phosphate	g	1,43	River	Primary	idem	71800[g]/50068[m3]	
Chloroform	mg	0,26	River	Primary	idem	13e3[mg]/50068[m3]	
Toluene	mg	0,02	River	Primary	idem	1e3[mg]/50068[m3]	
Phenol	mg	0,02	River	Primary	idem	1e3[mg]/50068[m3]	
Cd	mg	0,40	River	Primary	idem	20e3[mg]/50068[m3]	
Cu	mg	2,60	River	Primary	idem	130e3[mg]/50068[m3]	
Dioxins	ng	2,44	River	Primary	Measured		
Polychlorinated furans	ng	2,12	River	Primary	Measured		
Zn	g	0,30	River	Primary	Amount is calculated by dividing yearly emission between yearly m3 of effluent treated (2002)	5,24e6[g]/17252405[m3]	
Methanol	g	0,05	River	Primary	idem	0,78e6[g]/17252405[m3]	
Mn	g	0,25	River	Primary	idem	4,28e6[g]/17252405[m3]	
Wastes to treatment							
Water	ton	0,04	Effluent treatement plant	Primary	From primary sources: Wastewater = 375 gpm when treating 50068 m3/day.	375[gal/min]x3,785[L/gal]x1440[min/d] /1000[L/ton]/50068[m3/d]	
Sludge	kg	1,11	Sludge treatment	Primary	Amount is calculated by dividing yearly sludge generation between yearly m3 of effluent treated (2001)	20260[bdmt]/18206305[m3]x1000[kg/ton]	

SLUDGE TREATMENT

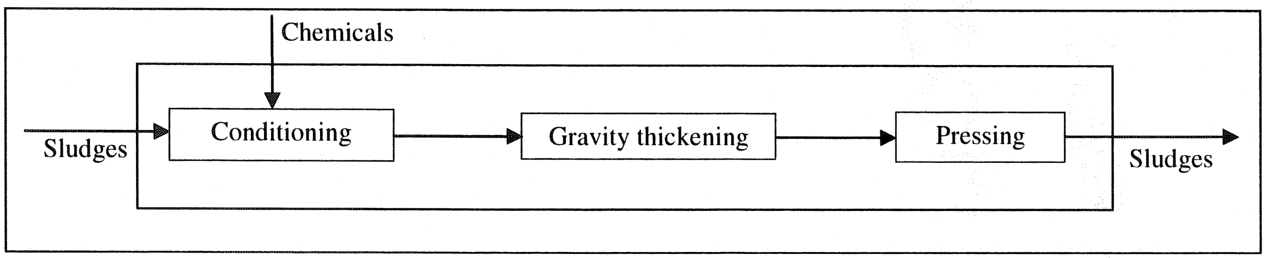

Figure C.7: Flowchart of the sludge treatment

Table C.7: Description of sludge treatment model

Unit process name: Sludge treatment							
Unit process description: Sludges dewatering							
Reference flow: 1 bdmt of sludges							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Waste treatment							
Sludges	bdmt	1,00	Newsprint mill				Reference flow
Materials/fuels							
Polyelectrolyte	kg	3,00	Suppliers	Primary	Measured		Refer to "chemicals organic ETH T"
Coagulant/flocculant	kg	0,80	Suppliers	Primary	idem		idem
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Wastes to treatment							
Sludge	ton	0,47	Industrial landfill	Primary	Calculated by dividing yearly amount of sludges landfilled between yearly amount of sludges treated	13175[ton]/28200[bdmt]	Average moisture content: 63%
Sludge	bdmt	0,83	Boiler house	Primary	Calculated by dividing yearly amount of sludges burned between yearly amount of sludges treated	23324[bdmt]/28251[bdmt]	Not entered in the software due to its format
Mass balance on wood: Sludges treated = sludges landfilled + sludges burned: 1[bdmt] = 0,47[ton]x0,37[bdmt/ton]+0,83[bdmt]							

BOILER HOUSE

Table C.8: Description of boiler house model

Unit process name: Boiler house							
Unit process description: Steam generation from combustion of natural gas, hog fuel and sludges in a boiler house							
Reference flow: 1 MMBTU (10^6 BTU)							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Resources							
Water	ton	0.28	River	Primary	From primary sources: Fresh water = 350 gpm. Assumption of 360 d/yr.	350[gal/min]x3.785[L/gal]x1440[min/d]x 360[d/yr]/1000[L/ton]/2441676[MMBTU/yr]	
Materials/fuels							
Natural gas	m^3	10.84	Suppliers	Primary	Amount is calculated by dividing yearly consumption between yearly steam generation in the boiler house	26456e3[m3]/2441676[MMBTU]	Model represents the pre-combustion inventory (natural gas production)
Hog fuel	bdmt	0.04	Sawmill	Primary	idem	93506[bdmt]/2441676[MMBTU]	
Chips rejects	kg	5.11	TMP	Primary	idem	40[kg rejects/bdmt TMPpulp]x 312059[bdmt TMPpulp]/2441676[MMBTU]	0% moisture content
NaOH	g	6.62	Suppliers	Primary	idem	16168e3[g]/2441676[MMBTU]	
H2SO4	g	85.12	Suppliers	Primary	idem	207833e3[g]/2441676[MMBTU]	
Trailer diesel	L	0.03		Primary	One way transportation. Fuel consumption calculated by multiplying total loads by average distance and considering a fuel efficiency of 2.55[km/L] (Ref. EPDS guidelines, 97)	2322[loads]x86.64[km]/2.55[km/L] /2441676[MMBTU]	
Electricity/heat							
Electricity	kWh	1.24		Primary	Amount is calculated by dividing yearly electricity consumption between yearly steam generation	22552000[kWh]/18206305[m3]	
Heat from natural gas	m^3	10.84		Primary	Same as natural gas in materials/fuels		Model represents combustion inventory. See table C.9
Heat from hog fuel	ton	0.09		Primary	Calculated amount of hogfuel plus chips rejects in materials/fuels, assuming an average moisture content of 50%	(0.04+5.11e-3)[bdmt]/0.5[bdmt/ton]	Model represents combustion inventory. See table C.10
Heat from sludge	ton	0.03		Primary	Amount is calculated by dividing yearly sludge diversion in the boiler house between yearly steam generation. Average moisture content: 63%	23324[bdmt]/0.37[bdmt/ton]/2441676[MMBTU]	idem
Outputs	**Unit**	**Amount**	**Destination**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Wastes to treatment							
Water	ton	0.12	Effluent treatement plant	Primary	From primary sources: Wastewater = 150 gpm. Assumption of 360 d/yr.	150[gal/min]x3.785[L/gal]x1440[min/d]x 360[d/yr]/1000[L/ton]/2441676[MMBTU/yr]	

Table C.9: Description of heat from natural gas (or natural gas combustion) model

Unit process name: Heat from natural gas

Unit process description: Natural gas combustion

Reference flow: 1 m^3 of natural gas

Outputs	Unit	Amount	Destination	Data source	Assumptions
Emissions to air					
CO2 (fossil)	kg	1,89	Atmosphere	Secondary: Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors	Based on data from chemical analysis of representative natural gas samples. Assumption: 99,5% combustion efficiency
Methane	g	0,04	Atmosphere		From a review of emission factors for combustion technologies and an analysis of combustion technologies
N2O	g	0,03	Atmosphere		
NOx (as NO2)	g	3,04	Atmosphere	Secondary: AP-42. Section 1,4 - Natural Gas Combustion. USEPA (1998)	Large wall-fired boilers - uncontrolled
CO	g	1,34	Atmosphere		
VOC	mg	0,09	Atmosphere		
SO2	mg	9,60	Atmosphere		100% conversion of fuel sulfur to SO2. Average sulfur content of 2000 grains/106 ft3
Particulates (PM2,5)	g	0,12	Atmosphere		100% particles are less than 1µm diameter

Table C.10: Description of heat from biomass (i.e., heat from hog fuel and heat from sludge) model

Unit process name: Heat from biomass (i.e. heat from hog fuel and heat from sludge)
Unit process description: Biomass combustion
Reference flow: 1 kg of biomass

Outputs	Unit	Amount	Destination	Data source	Calculation data / Assumptions	Calculations	Notes
Emissions to air							
Methane	g	0,05	Atmosphere	Secondary: Canada's Greenhouse Gas Inventory, 90-00, Appendix D: Emission Factors	From a review of emission factors for combustion technologies and an analysis of combustion technologies		
N2O	g	0,02	Atmosphere				
NOx (as NO2)	g	0,75	Atmosphere	Secondary: AP-42, Section 1.6 - Wood Residue Combustion in Boilers. USEPA (1998)	For bark/bark and wet wood/wet wood-fired boilers		
SO2	g	0,04	Atmosphere				
VOC	g	0,04	Atmosphere		From AP-42: 0,017[lb/MMBTU] and to convert to [lb/ton] multiply by (HHV x 2000) where HHV is the fuel heating value. HHV (MMBTU/lb) from primary sources: 1,25e-3(sludge) and 2,33e-3(hogfuel)	hog fuel: 0,017 x 2,33e-3 x 2000[lb/ton] / 2,2[g.ton/lb/kg] sludge: 0,017 x 1,25e-3 x 2000[lb/ton] / 2,2[g.ton/lb/kg]	Calculated value for sludge: 0,02
CO	g	1,42	Atmosphere	Primary	Averages (FY-01): 180,5 ppm of CO emission and 116829bdmt of biomass burnt. Boilers stack flow: 51,6m3/s (standard conditions). 360 operating days and 50% average moisture	180,5e-6[mol CO/mol gas] x 28[g CO/mol CO] x 51,6e3 [L.gas/s] / 24,45 [L.gas/mol gas] x 31104e3[s/yr] / 116829[bdmt/yr] x 0,5[bdmt/ton] / 1000 [kg/ton]	
Particulates (SPM)	mg	71,37	Atmosphere	Primary	38 kg/d of TSP when burning 95840,51 bdmt of biomass. 360 operating days and 50% average moisture	38e6[mg/d] x 360[d/yr] / 95840,51[bdmt/yr] x 0,5[bdmt/ton] / 1e3[kg/ton]	Enter to software TSP-PM10, i.e., 13,15 to avoid double counting in the impact assessment phase
Particulates (PM10)	mg	58,22	Atmosphere	Primary	idem. 31 kg/d of PM10	idem	idem. i.e., 1,88
Particulates (PM2,5)	mg	56,34	Atmosphere	Primary	idem. 30 kg/d of PM2,5	idem	
Waste to treatment							
Ashes	kg	0,05	Industrial landfill	Primary	Amount is calculated by dividing yearly ash generation between yearly amount of biomass burnt	11608[ton] / 116829[bdmt] x 0,5[bdmt/ton]	

ELECTRICITY

Table C.11: Description of the electricity model

Unit process name: Electricity							
Unit process description: Breakdown of the sources of the electricity used at the integrated newsprint mill (including sawmill)							
Reference flow: 1 MWh							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Materials/fuels							
Electricity Ontario	MWh	0,977	Ontario Power Generation (OPG)	Primary	Amount is calculated by dividing yearly electricity from the specific source between yearly electricity consumption	1070900[MWh]/1096334[MWh]	Refer to "Electricity Ontario" model See Table C.13
Co-generated Electricity	MWh	0,019	On-site generation			21213[MWh]/1096334[MWh]	Refer to "Co-generated electricity" model See Table C.12
On-site hydropower	MWh	0,004		Primary		4221[MWh]/1096334[MWh]	Modeled using FRANKLIN database (US average 95-99)

Table C.12: Description of the co-generated electricity model

Unit process name: Co-generated electricity							
Unit process description: On-site generated with turbo-generators							
Reference flow: 1 MWh							
Inputs	**Unit**	**Amount**	**Origin**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Electricity/heat							
Electricity	MWh	0,31		Primary	Amount is calculated by dividing yearly energy consumption between yearly electricity generation	6501[MWh]/21213[MWh]	
Steam on site	10^6BTU	4,02	Boiler house	Primary		85281[10^6BTU]/21213[MWh]	

Table C.12: Description of the Electricity Ontario model

Unit process name: Electricity Ontario

Unit process description: Electricity generation by Ontario Power Generation (OPG). Average power mix: 33%fossil (coal), 39%nuclear, 28%hydro.

Reference flow: 1 MWh

Inputs	Unit	Amount	Data source	Calculation data / Assumptions	Calculations	Notes
Resources						
Coal	lb	372,45	Secondary	Data calculated by modelig the average power mix with FRANKLIN database (US average, 95-99)		
Natural gas	lb	2,59	Secondary			
Crude oil	lb	0,52	Secondary			
Uranium	lb	0,01	Secondary			
Outputs	**Unit**	**Amount**	**Data source**	**Calculation data / Assumptions**	**Calculations**	**Notes**
Emissions to air						
CO2	kg	327,87	Primary	Amount is calculated by dividing yearly emission between yearly electricity generation. Source: GHG Action Plan,01	40e6[ton] / 122[TWh] / 1000[ton.kg/TWh/GWh]	Includes direct and indirect emissions
SO2	kg	1,23	Primary	Source: Environmental report, 2001		
NOX	kg	0,37	Primary	idem		
CO	g	100,73	Primary	Amount is calculated by dividing yearly emission between yearly electricity generation. Source: Ministry of Environment, 2002. See calculations in Table D.14		
VOC	g	4,60	Primary			
Particulates (TSP)	g	99,72	Primary			Entered to software TSP-PM10. i.e., 32,35 to avoid double counting in the impact assessment phase
Particulates (PM10)	g	67,37	Primary			idem. i.e., 40,18
Particulates (PM2,5)	g	27,19	Primary			
As	mg	7,13	Primary	Amount is calculated by dividing yearly emission between yearly electricity generation. Source: NPRI, 2001. See calculations in Table D.15		
Cu	mg	19,60	Primary			
Hydrazine	mg	1,07	Primary			
Zn	mg	38,50	Primary			
Pb	mg	5,98	Primary			
Cr(VI)	mg	8,61	Primary			
Hg	mg	4,76	Primary			
Ni	mg	10,10	Primary			
Co	mg	3,94	Primary			
H2SO4	g	6,52	Primary			
HF	g	4,26	Primary			
Dioxin(TEQ)	ng	9,51	Primary			
Hexachlorobenzene	ng	22,90	Primary			
HCl	g	72,98	Primary			
V	mg	14,70	Primary			
Mn	mg	9,26	Primary			
Ammonia	g	0,16	Primary			
Phenanthrene	ug	49,20	Primary			
Pyrene	ug	16,40	Primary			
Fluoranthene	ug	24,60	Primary			
Se	mg	95,70	Primary			
Benzo(k)fluoranthrene	ug	0,82	Primary			

Table C.13 (Cont'd): Description of the Electricity Ontario model

Outputs	Unit	Amount	Data source	Calculation data / Assumptions	Calculations	Notes
Emissions to water						
As	mg	0,42	Primary	Amount is calculated by dividing yearly emission between yearly electricity generation. Source: NPRI, 2001. See calculations in Table D.15		
Cu	g	0,11	Primary			
Hydrazine	mg	6,39	Primary			
Zn	mg	44,10	Primary			
Pb	mg	0,16	Primary			
Ni	ug	82,00	Primary			
Co	mg	0,66	Primary			
V	mg	0,82	Primary			
Mn	mg	2,71	Primary			
Cr(VI)	mg	4,10	Primary			
NH3	mg	73,40	Primary			
Suspended solids	kg	0,26	Secondary	Data calculated by modelig the average power mix with FRANKLIN database (US average, 95-99)		
Dissolved solids	g	69,50	Secondary			
BOD	mg	77,60	Secondary			Set to zero in LCA software to avoid double counting with BOD
COD	g	1,01	Secondary			
Phosphate	g	1,88	Secondary			
Emissions to soil						
Hg	mg	1,96	Primary	Amount is calculated by dividing yearly emission between yearly electricity generation. Source: NPRI, 2001. See calculations in Table D.15		
Dioxin(TEQ)	ng	0,49	Primary			
V	g	1,60	Primary			
Mn	g	1,40	Primary			
Cu	g	0,88	Primary			
Cr(VI)	g	1,05	Primary			
Ni	g	0,72	Primary			
Zn	g	0,74	Primary			
Pb	g	0,34	Primary			
As	g	0,21	Primary			
Co	g	0,31	Primary			
Phenanthrene	mg	0,75	Primary			
Pyrene	ng	98,40	Primary			
Benzo(a)anthracene	ng	90,20	Primary			
Benzo(e)pyren	ng	82,00	Primary			
Benzo[ghi]perylene	ng	82,00	Primary			
Fluoranthene	ng	65,60	Primary			
Benzo(b)fluoranthene	ng	73,80	Primary			
Benzo(a)pyrene	ng	49,20	Primary			
Dibenzo(a,h)anthracene	ng	24,60	Primary			
Indeno[1,2,3-cd]pyrene	ng	16,40	Primary			
Dibenzo(a,i)pyrene	ng	8,20	Primary			
Perylene	ng	8,20	Primary			
Se	mg	66,00	Primary			

Table C.14: Calculation of criteria pollutant emission from Ontario Power Generation

Source	Facility Name	CO	VOC	PM	PM10	PM2.5
Nuclear	Pickering			1,62		
Nuclear	Darlington			2,30		
Fossil	Atikokan	71,63	17,19	23,99	16,07	6,96
Fossil	Lakeview	1595,40	27,10	230,00	153,88	66,60
Fossil	Lambton	3251,60	106,97	3517,67	2422,01	818,19
Fossil	Lennox	238,06	54,21		1,96	1,27
Fossil	Nanticoke	6566,00	311,70	7475,80	5008,80	2168,00
Fossil	Thunder Bay	20,00	18,77	373,64	250,35	108,36
Total (ton)		11742,69	535,94	11625,02	7853,07	3169,37
netGWh		116571,43				
g/MWh		**100,73**	**4,60**	**99,72**	**67,37**	**27,19**

Source: Ministry of Environment (MOE) database. O.REG127/01, 2002

Table C.15: Calculation of NPRI emission from Ontario Power Generation.

Substance Name	tonnes			kg/MWh		
	Air	Land	Water	Air	Land	Water
Sulphuric acid	7,95E+02			6,52E-03		
Hydrogen fluoride	5,20E+02			4,26E-03		
Mercury	5,81E-01	2,39E-01		4,76E-06	1,96E-06	
Dioxines	1,16E-06	6,00E-08		9,51E-12	4,92E-13	
Hexachlorobenzene	2,79E-06			2,29E-11		
Hydrocloric acid	8,90E+03			7,30E-02		
Vanadium	1,79E+00	1,95E+02	1,00E-01	1,47E-05	1,60E-03	8,20E-07
Manganese	1,13E+00	1,71E+02	3,30E-01	9,26E-06	1,40E-03	2,71E-06
Copper	2,39E+00	1,07E+02	1,38E+01	1,96E-05	8,79E-04	1,13E-04
Chromium	1,05E+00	1,28E+02	5,00E-01	8,61E-06	1,05E-03	4,10E-06
Nickel	1,23E+00	8,79E+01	1,00E-02	1,01E-05	7,21E-04	8,20E-08
Zinc	4,70E+00	8,98E+01	5,38E+00	3,85E-05	7,36E-04	4,41E-05
Lead	7,30E-01	4,19E+01	2,00E-02	5,98E-06	3,44E-04	1,64E-07
Arsenic	8,70E-01	2,62E+01	5,00E-02	7,13E-06	2,15E-04	4,10E-07
Cobalt	4,80E-01	3,82E+01	8,00E-02	3,94E-06	3,13E-04	6,56E-07
Ammonia	2,00E+01		8,95E+00	1,64E-04		7,34E-05
Phenanthrene	6,00E-03	9,20E-02		4,92E-08	7,54E-07	
Pyrene	2,00E-03	1,20E-02		1,64E-08	9,84E-08	
Benzo(a) anthracene		1,10E-02			9,02E-08	
Benzo(e) pyrene		1,00E-02			8,20E-08	
Benzo(g,h,i) perylene		1,00E-02			8,20E-08	
Fluoranthene	3,00E-03	8,00E-03		2,46E-08	6,56E-08	
Benzo(b) fluoranthene		9,00E-03			7,38E-08	
Benzo(a) pyrene		6,00E-03			4,92E-08	
Dibenzo(a,h) anthracene		3,00E-03			2,46E-08	
Indeno(1,2,3-CD) pyrene		2,00E-03			1,64E-08	
Dibenzo(a,i) pyrene		1,00E-03			8,20E-09	
Perylene		1,00E-03			8,20E-09	
Selenium	1,17E+01	8,05E+00		9,57E-05	6,60E-05	
Hydrazine	1,30E-01		7,80E-01	1,07E-06		6,39E-06
Benzo(k) fluoranthene	1,00E-04			8,20E-10		

Source: National Pollutant Release Inventory (NPRI) database, 2001.

(Note: Net electricity production for the same reference year: 122.98 TWh)

TRANSPORTATION

Table C.16: Description of trailer diesel model

Unit process name: Trailer diesel				
Unit process description: Transportation in a tractor trailer truck				
Reference flow: 1000 gal of diesel fuel or 155319 t-km (Fuel efficiency=0,023 L/ton-km)				
Inputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Materials/fuels				
Destillate Fuel Oil	gal	1000		Reference flow
Outputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Emissions to air				
CO2 (fossil)	lb	22795,50	Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors for uncontrolled Heavy-Duty Diesel Vehicles (HDDV)	
Methane	lb	1,25		Based on technology tipically used in Canada
N2O	lb	0,67		idem
NOx	lb	106,55	From Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volume 2: Appendices A-S from Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 1993	
SO2	lb	6,66	Part 5: A program for Calculating Particle Emissions from Motor Vehicles from USEPA, Office of Mobile Sources, National Motor Vehicle and Fuels Emissions Laboratory	Parameters selected to the model: Year 2000; reformulated gasoline (sulphur content 0,0138% weight); 140 days of precipitation; 500 ft. altitude; vehicle included in an inspection and maintenance program
CO	lb	209,00	From Franklin database. US average technology, 1995-1999. Factors sourced on Mobile 5, the vehicle emission model by USEPA. Note: Database has been modified to include particulate size distribution.	
VOC	lb	37,70		
Particulates (PM10)	lb	29,80		Size distribution for diesel vehicles from Mobile model: PM2.5 = 92% PM10. Enter to software PM10=PM10-PM2,5 to avoid double counting during the impact assessment
Particulates (PM2,5)	lb	27,42		
Aldehydes	lb	5,50		
Organic substances	lb	116,00		

Table C.17: Description of locomotive diesel model

Unit process name: Locomotive diesel

Unit process description: Transportation by rail in a diesel powered locomotive

Reference flow: 1000 gal of diesel fuel or 608333 t-km (Fuel efficiency=0,007 L/ton-km)

Inputs	Unit	Amount	Data source	Assumptions
Materials/fuels				
Destillate Fuel Oil	gal	1000		Reference flow
Outputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Emissions to air				
CO2 (fossil)	lb	22795,50	Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors for diesel rail transportation	
Methane	lb	1,25		Based on technology tipically used in Canada
N2O	lb	9,18		idem
NOx	lb	106,55	From Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volume 2: Appendices A-S from Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 1993	
SO2	lb	6,66	Part 5: A program for Calculating Particle Emissions from Motor Vehicles from USEPA, Office of Mobile Sources, National Motor Vehicle and Fuels Emissions Laboratory	
CO	lb	130,00	From Franklin database. US average technology, 1995-1999. Factors sourced on Mobile 5, the vehicle emission model by USEPA. Note: Database has been modified to include particulate size distribution.	
VOC	lb	94,00		
Particulates (PM10)	lb	75,00		Size distribution for diesel vehicles from Mobile model: PM2.5 = 92% PM10. Enter to software PM10=PM10-PM2,5 to avoid double counting during the impact assessment
Particulates (PM2,5)	lb	69,00		
Aldehydes	lb	5,50		
Organic substances	lb	7,00		

Table C.18: Description of truck (single) gasoline model

Unit process name: Truck (single) gasoline				
Unit process description: Transportation by rail in a light-duty gasoline truck				
Reference flow: 1000 gal of gasoline				
Inputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Materials/fuels				
Gasoline	gal	1000		Reference flow
Outputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Emissions to air				
CO2 (fossil)	lb	19706,00	Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors for aged three-way catalyst light duty gasoline trucks	
Methane	lb	3,42		Based on technology tipically used in Canada
N2O	lb	8,35		idem
NOx	lb	34,82	From Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volume 2: Appendices A-S from Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 1993	
SO2	lb	1,27	Part 5: A program for Calculating Particle Emissions from Motor Vehicles from USEPA, Office of Mobile Sources, National Motor Vehicle and Fuels Emissions Laboratory	
CO	lb	528,00	From Franklin database. US average technology, 1995-1999. Factors sourced on Mobile 5, the vehicle emission model by USEPA. Note: Database has been modified to include particulate size distribution.	
VOC	lb	26,80		
Particulates (TSP)	lb	1,90		Size distribution for gasoline vehicles with catalyst from Mobile model: 89,5% PM2.5 and 97% PM10 Enter to software TSP=TSP-PM10 and PM10=PM10-PM2,5 to avoid double counting during the impact assessment
Particulates (PM10)	lb	61,50		
Particulates (PM2,5)	lb	56,74		
Pb	lb	0,03		
Organic substances	lb	171,00		

Table C.19: Description of propane vehicles model

Unit process name: Propane vehicles				
Unit process description: Transportation by propane vehicles				
Reference flow: 1000 L of LPG				
Inputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Materials/fuels				
LPG	L	1000		Reference flow
Outputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Emissions to air				
CO2 (fossil)	lb	1500,00	Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors for propane vehicles	
Methane	lb	0,52		Based on technology tipically used in Canada
N2O	lb	0,03		idem
NOx	lb	1,70	From Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, Volume 2: Appendices A-S from Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 1993	
SO2	lb	0,01	Part 5: A program for Calculating Particle Emissions from Motor Vehicles from USEPA, Office of Mobile Sources, National Motor Vehicle and Fuels Emissions Laboratory	

Table C.20: Description of aviation turbo model

Unit process name: Aviation turbo				
Unit process description: Air traffic (continental)				
Reference flow: 1000 gal Kerosene				
Inputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Materials/fuels				
Kerosene	gal	1000		Reference flow
Outputs	**Unit**	**Amount**	**Data source**	**Assumptions**
Emissions to air				
CO2 (fossil)	lb	21292,50	Canada's Greenhouse Gas Inventory, 90-00. Appendix D: Emission Factors for jet aircraft	
Methane	lb	0,67		Based on technology tipically used in Canada
N2O	lb	2,09		idem
NOx	lb	0,07	From air traffic continental by Idemat. European average, 90-94	
SO2	lb	0,01	idem	
CO	lb	0,01	idem	
CxHy	lb	0,02	idem	
Soot	lb	9,55E-05	idem	

FUEL PRODUCTION

Table D.21 shows a list of fuels used in different activities of the newsprint production life cycle as well as the secondary source (i.e., database) used for the fuel production models.

Table C.21: Reference of fuel production models

Fuel	Activity	Source
Natural gas	Steam generation	Franklin database US, average technology, 1995-1999
	Electricity generation (grid)	
Crude oil	Electricity generation (grid)	
Coal		
Kerosene I	Personnel transportation by plane	IDEMAT database. Europe, average technology, 1990-1994
LPG	Fork lift trucks	Franklin database US, average technology, 1995-1999
Gasoline	Personnel transportation by truck	
Diesel fuel oil	Mobile equipments; logs, chips, hog fuel and wastepaper supply; and newsprint distribution (truck)	
	Wastepaper supply and newsprint distribution (rail)	

The fuel production models with higher contributions (i.e., natural gas, diesel fuel oil and gasoline) were modified to include the following considerations:

- BOD was set to zero in order to avoid double counting with COD in the eutrophication impact category.
- Particle size distribution was included to improve the assessment on human health particles. Table D.22 presents the calculated data as well as the reference sources.

Table C.22: Calculated particulate size distribution for fuel production models.

Fuel	Unit	TSP	PM10	PM2.5	Assumptions/references
Natural gas	lb/1000cuft	0,0038	0,0038	0,0038	Particulates from compressor engines burning natural gas. Size distribution: 100% PM1 from AP-42, USEPA (1998)
Diesel fuel oil	lb/1000gal	1,6600	1,4276	0,9296	Particulates from boilers and cracking processes. It was assumed that the particle size distribution from industrial boilers firing residual oil can be representative for the whole process: 86%PM10 and 56%PM2.5. Ref: AP-42, USEPA (1995)
Gasoline	lb/1000gal	1,4200	1,2212	0,7952	

Note: To avoid double counting during the impact assessment, the values of PM10-PM2.5 has to be entered for PM10 and TSP-PM10 for TSP.

CHEMICAL PRODUCTION

Table C.23: Reference of chemical production models

Chemical	Unit Process	Source	Geography	Time	Technology	Notes
Borol	TMP	KCL	Finland	1996	Average	
SO_2	TMP, DIP	BUWAL250	Unspecified	Unspecified	Unspecified	
EDTA	TMP	ETH-ESU 96	Europe, W	1990 - 1994	Average	A general model gas used: Chemicals organic ETH
NaOH	TMP, DIP, boiler house	BUWAL250	Europe, W	1990 - 1994	Average	
H2O2	DIP, ETP	KCL	Europe	1992	Average	
NaSiO3	DIP	BUWAL250	Unspecified	1985 - 1989	Average	Data derived from literature references
Soap (stearic acid)	DIP	IVAM	Unspecified	Unspecified	Unspecified	
CaCl2	DIP	ETH-ESU 96	Europe, W	1990 - 1994	Average	A general model gas used: Chemicals inorganic ETH
Coagulant/flocculant	DIP, sludge treatment	ETH-ESU 96	Europe, W	1990 - 1994	Average	A general model gas used: Chemicals organic ETH
Biocide	DIP	ETH-ESU 96	Europe, W	1990 - 1994	Average	idem
Polyelectrolyte	Sludge treatment	ETH-ESU 96	Europe, W	1990 - 1994	Average	idem
H2SO4	Boiler house	ETH-ESU 96	Europe, W	1990 – 1994	Average	
Ammonia	ETP	ETH-ESU 96	Europe, W	1990 – 1994	Average	
Phosporic acid	ETP	ETH-ESU 96	Europe, W	1990 – 1994	Average	
Lime (CaO)	ETP	BUWAL 250	Mixed data	Mixed data	Mixed data	Data derived from literature references

Note: The models for chemicals with major contributions (e.g., Chemicals organic ETH) where modified setting BOD to zero to avoid double counting with COD in the assessment of eutrophication.

LANDFILL

Two landfill models were used in this study: the industrial landfill for process wastes (e.g. ashes) and the municipal landfill for wastepaper. Both landfill models were sourced on KCL and represents Finish averages from 1992. The model for industrial landfill was modified setting BOD to zero in order to avoid double counting with COD in the eutrophication assessment. The model for municipal landfill was only used for the scenario analysis.

APPENDIX D: SUBSTANCES NOT CHARACTERIZED BY THE SELECTED IMPACT ASSESSMENT METHODS

This appendix presents the substances that are part of the inventory in the system studied but that are not assessed by the selected models. These include:

1. **Raw materials**: The selected impact categories are only oriented towards the assessment of emissions. The choice of not including in this study input related impact categories for the assessment of use of resources or raw materials are explained in section 2.4 of Appendix A. A list of inventory results for this group of substances is presented in Table G.1 of Appendix G.

2. **Emissions to soil**: The selected impact categories do not assess emissions to soil. However, the total amount of releases is 20g which is small enough to assume that their effects are negligible. Furthermore, most of these substances are emitted from electricity production and according to the electricity company there is no evidence of a consequent negative impact to the environment. A list of inventory results for this group of substances is presented in Table G.5 of Appendix G.

3. **Non material emissions**: This group contains basically radioactive substances. At present, there is no available assessment model for this type of emissions, because they have potential effects mainly on the work environment which is not included on LCA studies. For the cases of radioactive wastes, their potential effects on the environment cannot be assessed because there is no available information about their disposal practices. A list of inventory results for this group of substances is presented in Table G.6 of Appendix G.

4. **Solid emissions**: A list of inventory results for this group of substances is presented in Table G.4 of Appendix G. Mill process permanent wastes (e.g., ashes) disposed in the on-site landfill represent 42,1% the total amount of solid emissions; their effects to the environment in terms of emissions to water (e.g.,

heavy metals) are considered negligible in the industrial landfill model. On the other hand, solid wastes emissions mainly from fuel production processes represent 10,7%; however, it is not possible to assess their potential effects in the environment since there is no additional information about the management of these wastes. Finally, other solid emissions represent less than 1% and so their potential effects can be considered negligible in comparison.

5. **Air emissions:** Most of the air emissions (i.e., 99,97%) are characterized and assessed by the selected models. Those not assessed are presented in Table D.1 along with their contributions to the total amount of air emissions; their potential effects are considered negligible due to their small contributions.

6. **Water emissions**: The most important water emissions are assessed by the selected methods. Those not assessed are presented in Table D.2. From them, the most significant in terms of mass are: dissolved solids (37,8%) that are emitted mainly from fuel production (i.e., 92.6%), due to its mineral nature we can assume that they have potential toxic effects and that they are already accounted for by metal characterization in the eco-toxicity impact category; total suspended solids (21,3%) that are emitted mainly in the newsprint mill effluent (65,5%), the effects of this emission are analysed in section 2.5 of Appendix A; salts (30,6%) that include basically sulphates and chlorides, because of their nature, the potential effects on the environment can be considered negligible. Finally, the effects of the remainder substances can be considered negligible due to their small contributions.

Table D.1: List of the air emissions not assessed and their contribution to the total amount of air emissions

Substance	Emission (kg/admt)	% cont.	Substance	Emission (kg/admt)	% cont.	Substance	Emission (kg/admt)	% cont.
organic substances	2,36E-01	2,13E-02	Mg	1,55E-05	1,40E-06	La	2,00E-08	1,80E-09
dust	2,35E-02	2,12E-03	K	1,17E-05	1,06E-06	U	1,43E-08	1,29E-09
H2SO4	1,69E-02	1,53E-03	alkenes	4,58E-06	4,13E-07	cyanides	1,38E-08	1,25E-09
aldehydes	1,55E-02	1,40E-03	Cl2	4,20E-06	3,79E-07	CFC-21	7,13E-09	6,43E-10
dust (coarse) process	3,22E-03	2,91E-04	Br	3,32E-06	3,00E-07	Sc	6,71E-09	6,06E-10
sulphur	9,75E-04	8,80E-05	Si	2,47E-06	2,23E-07	CxHy inc.	3,16E-09	2,85E-10
N2	7,37E-04	6,65E-05	kerosene	2,44E-06	2,20E-07	Soot	2,02E-09	1,82E-10
CxHy (non methane)	3,19E-04	2,88E-05	Ti	1,92E-06	1,73E-07	CxHy hal.	1,73E-09	1,56E-10
dust rough (s>10)	1,75E-04	1,58E-05	I	1,50E-06	1,35E-07	aerosols	1,58E-09	1,43E-10
silicates	1,56E-04	1,41E-05	Sr	6,80E-07	6,14E-08	Zr	1,07E-09	9,66E-11
He	8,11E-05	7,32E-06	H2	5,68E-07	5,13E-08	CF4	6,15E-10	5,55E-11
Ca	6,70E-05	6,05E-06	PAH's	4,35E-07	3,93E-08	CN (complex)	2,53E-10	2,28E-11
alkanes	4,53E-05	4,09E-06	Olefins (unspec.)	1,84E-07	1,66E-08	Pt	1,90E-10	1,71E-11
B	4,15E-05	3,74E-06	HCFC-21	1,71E-07	1,54E-08	dichloroethene	1,33E-10	1,20E-11
Fe	4,05E-05	3,65E-06	CxHy (alkanes)	1,04E-07	9,38E-09	dioxin (TEQ)	2,54E-11	2,29E-12
CxHy aromatic	3,24E-05	2,92E-06	ethyne	5,93E-08	5,35E-09	propionaldehyde	1,87E-11	1,69E-12
Na	3,11E-05	2,81E-06	CxHy (alkenes)	2,19E-08	1,98E-09	CFC (hard)	2,70E-12	2,44E-13
metals	2,61E-05	2,36E-06	benzo(k)fluoranthrene	2,12E-08	1,91E-09	CxHy (sulph)	1,62E-12	1,46E-13
nitrogen	2,11E-05	1,90E-06	n-nitrodimethylamine	2,08E-08	1,88E-09			

Table D.2: List of the water emissions not assessed and their contribution to the total amount of water emissions

Substance	Emission (kg/admt)	% total water emissions	Substance	Emission (kg/admt)	% total water emissions	Substance	Emission (kg/admt)	% total water emissions
dissolved solids	3,56E+00	3,78E+01	CxHy aromatic	5,51E-05	5,85E-04	chromate	5,34E-07	5,67E-06
sulphate	2,56E+00	2,72E+01	triethylene glycol	4,16E-05	4,42E-04	AOX	2,84E-07	3,02E-06
suspended solids	2,01E+00	2,13E+01	fluoride ions	2,92E-05	3,10E-04	glutaraldehyde	2,39E-07	2,54E-06
Cl-	3,19E-01	3,39E+00	VOC as C	2,00E-05	2,12E-04	tributyltin	7,99E-08	8,48E-07
acids (unspecified)	1,09E-01	1,16E+00	salt	1,78E-05	1,89E-04	AOCl	7,00E-08	7,43E-07
oil	6,02E-02	6,39E-01	HOCL	9,29E-06	9,87E-05	Cs	5,74E-08	6,10E-07
Na	3,87E-02	4,11E-01	OCl-	9,18E-06	9,75E-05	P-compounds	5,23E-08	5,55E-07
dissolved substances	1,29E-02	1,37E-01	acid organic (as C)	9,04E-06	9,60E-05	W	5,00E-08	5,31E-07
other organics	9,65E-03	1,02E-01	Acid as H+	8,94E-06	9,49E-05	acenafthylene	4,19E-08	4,45E-07
suspended substances	7,46E-03	7,92E-02	alkanes	7,89E-06	8,38E-05	CxHy chloro	2,97E-08	3,15E-07
undissolved substances	7,08E-03	7,52E-02	CxHy	7,63E-06	8,10E-05	olefines	2,16E-08	2,29E-07
Fe	3,57E-03	3,79E-02	I	5,90E-06	6,27E-05	CxHy aliphatic	1,92E-08	2,04E-07
calcium ions	3,55E-03	3,77E-02	H2	4,48E-06	4,76E-05	S	4,75E-09	5,04E-08
salts	2,94E-03	3,12E-02	calcium compounds	4,17E-06	4,43E-05	chlorinated solvents (unspec.)	3,80E-09	4,04E-08
baryte	1,93E-03	2,05E-02	detergent/oil	3,21E-06	3,41E-05	Ce	1,76E-09	1,87E-08
anorg. dissolved subst.	1,76E-03	1,87E-02	sulphide	2,50E-06	2,65E-05	dimethyl p-phthalate	6,40E-10	6,80E-09
fats/oils	1,57E-03	1,67E-02	nitrite	4,54E-03	4,82E-02	dioxins (TEQ)	1,11E-10	1,18E-09
Mg	1,02E-03	1,08E-02	dissolved organics	1,83E-06	1,94E-05	dibutyl p-phthalate	1,02E-10	1,08E-09
metallic ions	7,98E-04	8,47E-03	Si	1,29E-06	1,37E-05	Polychlorinated furans (PCDF)	9,64E-11	1,02E-09
K	6,31E-04	6,70E-03	triethyleneglycol	1,28E-06	1,36E-05	dimethylphtalate	2,67E-11	2,84E-10
Sr	3,71E-04	3,94E-03	SO3	1,20E-06	1,27E-05	di(2-ethylhexyl)phthalate	5,60E-12	5,95E-11
B	3,42E-04	3,63E-03	acenaphthylene	1,00E-06	1,06E-05	dibutylphthalate	4,24E-12	4,50E-11
fatty acids as C	2,99E-04	3,18E-03	PAH's	9,96E-07	1,06E-05	asbestos	1,04E-12	1,10E-11
H2SO4	8,44E-05	8,96E-04	cyanide	7,50E-07	7,96E-06	hydroxy (ions)	5,41E-13	5,74E-12
Ca	8,40E-05	8,92E-04	alkenes	7,30E-07	7,75E-06	titanium(IV)oxide	1,45E-14	1,54E-13
Ti	6,59E-05	7,00E-04	Ru	5,90E-07	6,27E-06	oil (animal/vegetable)	4,27E-15	4,53E-14

APPENDIX E: UNCERTAINTY RANGES FOR SELECTED KEY PARAMETERS

This appendix presents detailed data on the uncertainty ranges for the selected key parameters. See section 3.3 of Appendix A for explanation on the references used.

PROCESS DATA FOR THE INTEGRATED MILL

Table E.1: Uncertainty ranges for mill process data

Input Parameter	Unit	Baseline	Min	Max
Electricity consumption	MJ/admt	9520,00	8710,00	11300,00
Natural gas consumption	m^3/admt	65,00	35,30	102,00
Biomass consumption	kg/admt	615,00	418,70	678,00
EDTA consumption	kg/admt	0,82	0,67	1,00
H_2O_2 consumption	kg/admt	2,18	1,36	2,93
NaOH consumption	kg/admt	4,34	2,37	6,48
Solids to landfill	kg/admt	73,80	32,90	103,00
Fuel for transportation	L/admt	9,00	2,00	26,00
N-t from newsmmill effluent	g/admt	183,00	103,00	203,00

DATA ON ELECTRICITY PRODUCTION

Table E.2: Uncertainty ranges for data on electricity production (Electricity Ontario model)

Input Parameter	Unit	Baseline	Min	Max
CO_2 from Electricity Ontario	kg/MWh	327,87	262,30	393,44
SO_2 from Electricity Ontario	kg/MWh	1,23	0,98	1,48
NO_X from Electricity Ontario	kg/MWh	0,37	0,30	0,44
Hg from Electricity Ontario	mg/MWh	4,76	2,38	7,14
As-a from Electricity Ontario	mg/MWh	7,13	3,57	10,70

DATA SOURCED ON FRANKLIN DATABASE

Table E.3: Uncertainty ranges for secondary data sourced on FRANKLIN database

Input Parameter	Unit	Baseline	Min	Max
SO_2 from natural gas production	lb/1000 cft	1,99	1,59	2,39
VOC from natural gas production	lb/1000 cft	0,53	0,37	0,69
Cd-w from natural gas production	lb/1000 cft	1,40E-04	2,80E-05	2,52E-04
Hg emission from coal into electricity boilers (in borol and H_2O_2 production)	lb/1000 lb	6,60E-05	1,32E-05	1,19E-04
PM2.5 from Trailer diesel	lb/1000 gal	27,42	21,93	32,90

SECONDARY DATA FROM PROCESSES AVAILABLE IN ALTERNATIVE DATABASES

Table E.4: Uncertainty ranges for secondary data with similar process

Input Parameter	Unit	Baseline	Min	Max
NO_X from heat from biomass	g/kg	0,75	0,45	1,40
NO_X from heat from natural gas	g/m^3	3,04	1,60	5,00
CO_2 from heat from natural gas	g/m^3	1891,00	1888,00	1972,00

SECONDARY DATA WITH NO AVAILABLE INFORMATION ON UNCERTAINTY AND NOT INCLUDED IN ALTERANTIVE DATABASES

Table E.4: Uncertainty ranges for secondary data with no available information on uncertainty and not included in alternative databases

Input Parameter	Unit	Baseline	Min	Max
CH4 from industrial landfill	kg/ton	53,00	5,30	530,00
Halon-1301 from EDTA production	ug/kg	100,00	10,00	1000,00
CFC-114 from EDTA production	ug/kg	223,00	2,23	2230,00
As-w from NaOH production	g/ton	0,64	0,01	64,00

APPENDIX F: PEER REVIEW REPORT

RAPPORT FINAL DE REVUE CRITIQUE

Titre de l'étude :	Life Cycle Assessment of Newsprint Production at an Integrated Mill
Auteur(s) :	Erica Salazar
Mandataire(s) :	NSERC Environmental Design Chair in Process Integration, Valorisation Recherche Quebec (VRQ), Tembec – Spruce Falls mill
Comité d'évaluation :	Julie Godin Pascal Lesage Jean-François Ménard
Année de réalisation de l'étude :	2003

La Section 1 de ce rapport reprend intégralement les commentaires apportés par les évaluateurs (E) lors de la revue critique préliminaire ainsi que les réponses de l'auteur (A) à ces commentaires. Lorsque nécessaire, des remarques ont été ajoutés en italique aux réponses de l'auteur lors de la revue critique finale (E2). Une absence de commentaire indique que le comité adhère au point de vue de l'auteur. La Section 2 de ce rapport présente les commentaires du comité effectués lors de la revue critique finale (E2).

SECTION 1 :
RAPPORT DE REVUE CRITIQUE PRELIMINAIRE ET COMMENTAIRES DU COMITE DE REVUE (SI APPLICABLE):

1. E) Reformuler l'objectif de l'étude afin d'insister sur l'identification des processus élémentaires les plus dommageables du point de vue environnemental (hot spot identification).

   A) The objectives of the LCA study have been explicitly stated as "the identification of opportunities of the integrated mill to improve the life cycle environmental performance of newsprint production". However, it has also been indicated the future intended applications of the baseline model in the assessment of the process variants.

2. E) Préciser que le travail devra subir des modifications avant d'être utilisé comme ouvrage de base (baseline) pour l'évaluation de l'effet de changements apportés au système de production de papier journal. Documenter et identifier les modifications requises.

   A) These modifications have been identified and recommended for future applications in the experimental part of the study. See Part II, Section 5.4.

   E2) *Nous recommandons d'ajouter les modifications nécessaires à l'Appendixe A également.*

Champ de l'étude

1. E) Un flux de référence devrait être identifié ;

   A) The functional unit was reformulated as "the production of 1 admt (i.e., 1 air dried metric ton, 10% moisture content) of standard newsprint with 20% recycled content" (See Section 2.1 of Appendix A). This reformulation distinguishes the functional unit from the reference flow which is 1 admt of newsprint.

2. E) La frontière temporelle du système de produit devrait être identifiée. Celle-ci doit être cohérente pour l'ensemble du système de produit. Cette frontière permettra d'identifier la période d'émission des différents processus, tel l'enfouissement sanitaire ;

A) The model for industrial landfill was sourced from KCL-ECO. We got in contact with them and they expressed that there is no time dependency included in their model. Additional details on data calculation were not provided.

E2) Les émissions d'un site d'enfouissement ont forcément une dépendance au temps, sinon il faudrait réévaluer la qualité de ce modèle. Nous recommandons d'ajouter la référence bibliographique (référence à un document ou un site internet) de KCL-ECO dans le mémoire et à l'Appendixe C (sous landfill).

3. E) Identifier les frontières temporelles (si applicable) des modèles utilisés pour chacune des catégories d'impact ;

A) Temporal boundaries have been defined for the models of global warming (i.e., 100 years) and ozone depletion (i.e., infinite). They have been documented in Section 2.4 of Appendix A.

4. E) Choix des catégories d'impacts : certaines catégories qui pourraient être pertinentes à l'étude ne sont pas considérées, telle l'utilisation de ressources (eau, bois, etc.). Des justifications devraient être fournies dans le rapport final.

A) The selection of impact categories, category indicators and characterization factors is justified and documented in Section 2.4 of Appendix A. Furthermore, the exclusion of some relevant impact categories is mentioned as a limitation in the experimental part and recommendations for the analysis of their inclusion in future studies based on the baseline model are given.

E2) Nous recommandons de discuter de l'effet de l'exclusion de ces catégories d'impact sur les résultats de la présente étude (hot spot identification) et lors de l'utilisation visée (baseline) (i.e : l'exclusion de ces catégories d'impacts pourrait-elle inverser une décision ? est-ce une limite à la présente étude ?)

Analyse de l'inventaire

1. E) Certains processus considérés dans l'inventaire ne sont pas liés de façon linaire avec l'unité fonctionnelle, mais sont traités comme tel (ex : énergie et déchets consommés par les activités administratives de l'usine). Ces processus devraient être identifiés dans le rapport final ainsi que les modes de traitement des données;

   A) These activities have been identified and documented and an analysis of their inclusion has been recommended for the future applications of the baseline model (See Part II, Section 5.2). Explanations about the data treatment are presented in Appendix C.

2. E) Transport par camion : les trajets d'aller et de retour devraient être considérés, à moins d'avoir une raison et de la préciser dans le rapport final (ex : trajet de retour utilisé pour transporter d'autres matériaux n'étant pas considérés dans le système de produit).

   A) All the assumptions made in transportation modeling are presented and justified in Section 2.5 of Appendix A.

3. E) Vérifier que les considérations méthodologiques utilisées sont constantes pour le traitement des processus de transport;

A) Methodological choices for transportation are consistently applied as it is shown in Appendix C.

4. E) Documenter les données relatives au transport (ex : en appendixe) et donner un exemple de calcul afin d'augmenter la transparence. Documenter les trajets (aller/retour) considérés pour chaque processus de transport;
A) All the data used in transportation modeling is presented in Appendix C as well as calculation examples and assumptions made.

5. E) Les données primaires devraient être documentées de façon transparente dans le rapport final. Par exemple, les processus élémentaires pourraient être présentés en appendixe, pour chacun, la fonction serait définie, les entrants et sortants (quantitatif), les hypothèses de calculs, etc.;
A) This information is included in Appendix C.

6. E) Le type de données (donnée générique, de site, etc.) utilisée pour chaque processus élémentaire devrait également être identifié;
A) This information is included in Appendix C.

7. E) Recyclage municipale: les heures de fonctionnement du camion de collecte des matières résiduelles devrait être modifiées de manière à refléter la réalité (heures de fonctionnement du camion ≠ 24 par jour) ;
A) This is a conservative approach for the calculation of the contribution of wastepaper collection to the category indicator results. The consequent results are negligible for all the impact categories (<<1%). Therefore, a modification to reflect the reality is not necessary because it wouldn't change this conclusion.

8. E) Un vocabulaire anglais existe dans la littérature ACV pour nommer les variables directes, c'est-à-dire sous le contrôle de l'entreprise, et indirectes, soit sans contrôle : foreground et background (Réf : Adisa Azapagic and Roland Clift, 1999. Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 7, 101–119).

   A) This terminology is used and explained in the document. See for example Appendix A.

Évaluation des impacts du cycle de vie

1. E) Les substances non identifiées par la méthode d'EICV devraient être rapportées dans le rapport final, ainsi que la masse totale (ou %) qu'elles représentent par rapport à l'ensemble des émissions du système de produits. De plus, l'effet potentiel de leur exclusion devrait être évalué, du moins qualitativement.

   A) This analysis is presented in Appendix D.

Interprétation du cycle de vie :

1. E) Étude de sensibilité sur la variation des gridmix : les données utilisées pour évaluer les entrants et sortants associés aux différentes sources d'énergie sont limitées (i.e. : dans la base de donnée Franklin, le processus hydropower à pour entrant l'énergie potentielle de l'eau et aucun sortants). Il est alors recommandé de parler des limites associées à l'utilisation de telles données. Également, en raison de ces limites, toute interprétation en fonction du contexte géographique devrait être évitée. Pour limiter les interprétations géographiques, il est recommandé de parler en terme de sources d'énergie plutôt qu'en terme de provinces ;

A) The references on provinces are maintained for illustrative purposes. However, it has been explicitly documented that the results reflect the dramatic effect of the electricity model on the category indicator results as opposed to similar systems in these provinces. See Appendix B.

E2) Nous recommandons :

- *D'ajouter, en tant que limites à cette étude, la faible qualité des données utilisées, et ce à deux endroits : à la Section 6.3.3 (Partie II) et à l'Appendixe B.*
- *De mentionner que les sources de données utilisées pour le gridmix énergétique ontarien sont différentes entre l'étude de sensibilité et la 'baseline'.*
- *D'indiquer clairement, afin d'augmenter la transparence, ces sources données à l'Appendixe B.*
- *De présenter à l'Appendixe C les données utilisées pour l'étude sur la variation des gridmix.*

2. E) Augmenter le niveau de transparence. Pour ce faire, voici quelques recommandations: Expliquer le détail des analyses de contribution dans le rapport final et donner un exemple de calcul. Expliquer les agrégations réalisées lors des analyses de contribution ;

   A) This information is presented in Appendix H.

3. E) Expliquer les facteurs de corrections appliqués lorsque la somme des processus élémentaires contribuant à un impact n'était pas égale à 100% ;

   A) These correction factors were applied due to some software's rounding errors. However, these latter do not affect the results, therefore correction factors were not applied on the contributions presented in Appendix H.

   E2) Contributions aux impacts :

- *De plus, nous recommandons d'expliquer à ce moment et non dans le rapport de revue critique pourquoi la somme des contributions ne totalisent pas 100% pour l'ensemble des catégories d'impacts (ex : ≠100% pour la destruction de la couche d'ozone).*

4. E) Éviter ou documenter les changements de noms effectués lors des analyses (ex : lors de l'analyse de contribution dans Global warming (CO2), le processus élémentaire 'Heat from natural gas' change de nom pour 'Steam from gas') ;

   A) The change of name in some cases is only for purposes of better understanding of the results presented in the main body of the study. However in Appendix H, the model names as they are in the used software are presented in italics along with the name used in main body.

5. E) Expliquer le calcul des indicateurs de la qualité des données (DQI) et donner un exemple. Préciser les valeurs des DQI individuels (non agrégés) dans le rapport final. Expliquer dans le rapport final comment il est possible d'attribuer un seul DQI, alors que les processus élémentaires, proviennent probablement de différentes sources (i.e. : la plupart du temps, les processus élémentaires au sein d'une seule classe proviennent de la même base de donnée, pour lesquelles l'auteur attribue des DQI équivalents. Si dans certains cas les processus proviennent de plusieurs bases de données, le DQI identifié dans le rapport est celui pour le processus contribuant de façon plus importante. Dans le cas spécifique de production de substances chimiques, les DQI sont tous >2 indépendamment de leurs provenance : pour ce cas, il est décidé de mettre la mention >2 plutôt que le DQI du processus contribuant le plus).

   A) The calculation of DQI is explained in Section 3.2 of Appendix A. No aggregation is anymore applied in the DQI results in the final version of the study. This latter modification did not affect the selection of key parameters for the performance of sensitivity analyses.

6. E) Préciser l'origine du critère de cut-off pour qu'une donnée passe de High à Low Uncertainty (2) et de celui utilisé pour qu'une contribution passe de High à Low (10) dans le rapport final ;
A) This criterion is based in a literature reference which has been documented in Section 3.2 of Appendix A.

7. E) Il est écrit que la quantité de boue pour les 3 scénarios est la même. Précisez les raisons dans le rapport final (i.e. : les données ne sont pas disponibles actuellement, car il s'agit d'une technologie émergeante. Seule l'eutrophisation est considérée pour cette analyse et la quantité de boue n'influence pas cette catégorie d'impact). Par contre, dans les ACV futures, cette hypothèse devra être revue et corrigée.
A) This issue is identified and justified in Section "Effluent Reduction Scenarios" of Appendix B.

SECTION 2 : NOUVELLES REMARQUES RELATIVES A DES ELEMENTS NON EVALUES LORS DE LA REVUE PRELIMINAIRE :

Généralités :

1. *E2) Le Chapitre 6 du mémoire fait de nombreuses références à des sections précises de l'Appendixe B. Or l'Appendixe B ne présente pas une division en sections.*
2. *E2) Pour faciliter la compréhension, définir certains termes, tels DIP, TMP etc., au début de chacun des deux articles.*
3. *E2) Appendixe A, Section 3.1, il est écrit "For one-product assessment (also called attributional LCA), when the purpose is usually the identification of improvement opportunities, three numerical analyses are proposed: contribution, perturbation, and uncertainty (Heijungs et al. 2001)." La différence entre les deux modes d'ACV (attributional et consequential) ne se limite pas au nombre de produits comparés. Nous suggérons de soit enlever la mention du terme attributional dans le texte (préféré), soit d'expliquer plus tôt dans le texte la différence entre ces deux modes d'analyse.*
4. *E2) Appendixe A, Section 3.7, il est écrit "Examples of methodological choices that introduce uncertainty to LCA models are: the selection of functional unit, the system boundaries, the allocation rules, the choice of using <u>average</u> data or <u>average</u> technology, and the selection of characterization methods (Bjorklund 2002)." Nous recommandons:*
   a. *de changer le mot ARE par le mot INCLUDE ; et*
   b. *de s'assurer que le texte ne devrait pas lire "choice between average and marginal technology/data"?*

Objectifs et champ de l'étude

1. *E2) Revue critique (Partie II, Section 5.5), nous recommandons de préciser que la revue critique finale (effectuée à partir de la thèse) concerne*

uniquement les éléments méthodologiques relatifs à la tenue d'ACV. De plus, nous recommandons de préciser le niveau de détail de la revue critique (i.e. seulement environ 10% des calculs ont été révisés).

2. *E2) Les processus élémentaires illustrés dans la figure représentant le système de produits (Figure 2 de l'Appendixe B) ne correspondent pas à ceux définis et utilisés dans l'ACV. Nous recommandons de reprendre la figure et de ne présenter que les processus élémentaires pour lesquels des données d'inventaires sont collectés (i.e. les sous-processus de celui de TMP ne sont pas utiles et portent même à confusion car ils sont par la suite aggrégés lors du calcul de l'inventaire). Nous recommandons également de clairement représenter les frontières du système de produits afin de bien illustrer les processus inclus dans l'étude.*

Analyse de l'inventaire

1. *E2) Appendixe A, Section 2.1, il est mentionné que "It was assumed that newspaper printing, use, and disposal could be excluded from the study because newsprint production process variants do not significantly affect the environmental impacts due to these stages. For instance, an increase in the recycled content of newsprint can affect the printability and appearance properties of newspapers in pressrooms, and consequently, more ink can be required (Smook 1992). However, these effects were considered negligible compared to those involved with the process modification.". Nous recommandons d'appuyer cette affirmation par une référence bibliographique ou des calculs.*
2. *E2) Les données manquantes à l'étude devraient être clairement rapportées (si applicable). Si applicable, l'effet de leur exclusion devrait être traité ?*
3. *E2) Appendixe B, Section Inventory Analysis, les Figures 3, 7, 8 9 et 15 ne sont pas claires quant au système d'unités utilisé (par exemple pour la*

Figure 3, quelle est l'unité utilisée pour l'axe des ordonnées et que signifient les quantités entre parenthèses sur l'axe des abscisses (ex : CO2 (200 kg)).

4. *E2) Appendixe B, Section Inventory Analysis, pourquoi les résultats d'inventaire pour la production d'électricité sont-ils en équivalents CO2 ? les données brutes, non caractérisées n'étaient pas disponibles ? cette agrégation peut avoir d'importantes conséquences dans l'analyse de contribution.*

5. *E2) Appendixe B, Section Inventory Analysis, nous recommandons de supporter l'affirmation que les métaux Zn et Mn sont des constituants naturels du bois et pas les autres métaux, par une référence bibliographique.*

5. *E2) Indiquer clairement, à l'Appendixe C, si les imputations sont massiques ou volumiques.*

Évaluation des impacts du cycle de vie

1. *E2) Partie II, Section 6.3.3 c), il est indiqué que les résultats normalisés sont rapportés à la Section 6.3 de l'Appendixe B.*
   - *D'une part, nous recommandons d'indiquer à cet endroit (Section 6.3.3 c)) la référence de normalisation (i.e. par rapport au baseline) pour ne pas porter à confusion le lecteur.*
   - *D'autre part, pour l'Appendixe B, lorsque les résultats sont normalisés (ce qui n'est pas toujours le cas) indiquer le dans le titre du tableau. La référence de normalisation (baseline) devrait également être ajoutée dans le titre du tableau.*
   - *La Section 6.3 de l'Appendixe B n'existe pas.*

2. *E2) Appendixe B, Section Impact Assessment, le commentaire suivant : ''the large number of inventory indicators has been reduces to 9'' porte à confusion. Le Tableau 1 présentait déjà 9 catégories et indicateurs. S'il est fait référence à la conversion des résultats d'inventaire en unités communes*

(celles des 9 indicateurs de catégories d'impact), soit à la caractérisation, nous recommandons de reformuler.

Interprétation du cycle de vie :

1. *E2) Appendixe B, aucune limite d'interprétation ou critiques à la méthodologie ne sont rapportées dans le cadre de la discussion (ex : qualité des données utilisées, choix des catégories d'impact).*

NB : Cette revue critique s'applique uniquement aux aspects méthodologiques relatif à la tenue d'ACV, ainsi qu'aux calculs effectués dans le cadre d'ACV. Les aspects méthodologiques relatifs à la rédaction d'un mémoire de maîtrise ne sont pas l'objet de la présente revue. Ainsi plusieurs éléments sont laissés à la discrétion de l'auteur et des membres du jury. Les recommandations issues de ce rapport sont issues de la série de normes ISO 14 040 et de lignes directrices internes au CIRAIG pour la conduite d'ACV.

APPENDIX G: INVENTORY ANALYSIS RESULTS

RAW MATERIALS

Table G.1: Life cycle inventory results – raw materials

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Air	kg	5,44	iron (Fe)	g	1,21	potential energy water ETH	MJ	3,68
Barite	g	9,61	iron (in ore)	g	35,20	process and cooling water	l	23,00
Bauxite	g	1,89	iron (ore)	g	2,02	reservoir content ETH	m3y	0,08
Bentonite	g	1,67	lead (in ore)	mg	83,20	rhenium (in ore)	ng	719,00
Chlorine	pg	4,68E-08	lead (Pb)	mg	2,75	rhenium (Re)	ng	4,17
chromium (Cr)	mg	1,54	lignite (8.1 MJ/kg) ETH	g	5,23	rhodium (in ore)	ng	719,00
chromium (in ore)	mg	70,70	lignite ETH	kg	1,54	rhodium (Rh)	ng	4,39
Clay	g	3,64	limestone	g	462,00	rock salt	kg	2,56
clay minerals	mg	79,70	lubricant	mg	2,27	sand	kg	1,53
Coal	mg	765,00	lubricating oil	mg	227,00	sand, clay	mg	867,00
coal (18 MJ/kg) ETH	g	113,00	manganese (in ore)	mg	19,40	silver (Ag)	µg	120,00
coal (27.1 MJ/kg)	mg	547,00	manganese (Mn)	µg	747,00	silver (in ore)	mg	3,59
coal (29.3 MJ/kg)	mg	2,35	marl	g	31,00	soda	kg	2,56
coal ETH	kg	1,69	material known, no data	kg	5,88	sulphur	kg	3,18
coal FAL	kg	440,00	material unknown	µg	391,00	tin (in ore)	mg	1,99
cobalt (Co)	ng	90,70	methane (kg) ETH	g	4,63	tin (Sn)	µg	66,30
cobalt (in ore)	ng	132,00	mining gas (30,3 MJ/kg) ETH	mg	276,00	turbine water ETH	m3	19,40
copper (Cu)	mg	22,00	molybdene (in ore)	ng	568,00	uranium (in ore)	mg	57,80
copper (in ore)	mg	780,00	molybdenum (Mo)	ng	19,60	uranium (in ore) ETH	mg	56,40
crude oil	g	10,00	Na	kg	6,61	uranium (U)	µg	664,00

Table G.1 (Cont'd): Life cycle inventory results – raw materials

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
crude oil (41.9 MJ/kg)	µg	666,00	natural gas	g	9,22	waste paper (feedstock)	kg	197,00
crude oil (42,6 MJ/kg) ETH	g	38,00	natural gas (35,0 MJ/m3) ETH	l	87,10	water	kg	142,00
crude oil (42,7 MJ/kg) IDEMAT	mg	17,40	natural gas (36,6 MJ/m3; vol)	l	28,40	water (cooling)	kg	100,00
crude oil ETH	kg	1,48	natural gas (vol)	l	520,00	water (process)	kg	4,57
crude oil FAL	kg	21,50	natural gas ETH	m3	3,13	water (sea)	g	86,00
crude oil IDEMAT	g	154,00	natural gas FAL	kg	66,30	water (sea, for processing)	g	2,15
energy (undef.)	kJ	5,02	nickel (in ore)	mg	45,00	water (surface)	tn.lg	43,90
energy from coal	kJ	15,10	nickel (Ni)	µg	771,00	water barrage (vol)	cm3	109,00
energy from hydro power	MJ	40,90	nickel (ore)	g	35,50	water turbine	l	26,20
energy from natural gas	MJ	2,63	palladium (in ore)	ng	678,00	wood	tn.lg	1,03
energy from oil	kJ	5,50	palladium (Pd)	ng	4,12	wood (dry matter) ETH	g	10,50
energy from uranium	kJ	36,70	petroleum gas ETH	l	78,20	wood/wood wastes FAL	g	40,00
gas (35MJ/m3); from oil prod.	cu.in	158,00	platinum (in ore)	ng	763,00	zeolite	µg	44,60
gravel	g	137,00	platinum (Pt)	ng	4,72	zinc (in ore)	mg	2,03
H3BO3	kg	4,56	pot. energy hydropower	MJ	3,17	zinc (Zn)	µg	87,40
NaCl	mg	13,80	uranium FAL	g	5,97			

AIRBORNE EMISSIONS

Table G.2: Life cycle inventory results – airborne emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
1,2-dichloroethane	µg	6,81	cyanides	µg	13,80	nitrogen	mg	21,10
acetaldehyde	mg	4,92	dichloroethane	µg	116,00	NO	µg	15,00
acetic acid	mg	22,40	dichloroethene	ng	133,00	NO2	mg	1,50
acetone	mg	4,91	dichloromethane	µg	432,00	non methane VOC	g	866,00
acetylene	µg	1,24	Dinitrogen oxide	mg	179,00	NOx	kg	1,93
acrolein	µg	98,10	dioxin (TEQ)	ng	25,40	Nox (as NO2)	g	255,00
aerosols	µg	1,58	dust	g	23,50	Olefins (unspec.)	µg	184,00
Al	mg	46,40	dust (coarse) process	g	3,22	organic substances	g	236,00
aldehydes	g	15,50	dust (PM10) mobile	mg	59,40	P-tot	µg	638,00
alkanes	mg	45,30	dust (PM10) stationary	g	2,35	PAH's	µg	435,00
alkenes	mg	4,58	dust (SPM)	mg	69,10	particulates (PM10)	g	116,00
ammonia	g	3,90	dust rough (s>10)	mg	175,00	particulates (PM2.5)	g	223,00
arsenic	mg	18,40	ethane	mg	558,00	particulates (SPM)	g	93,40
As	mg	1,22	ethanol	mg	9,83	particulates (unspecified)	g	4,93
B	mg	41,50	ethene	mg	25,20	Pb	mg	21,90
Ba	µg	692,00	ethylbenzene	mg	5,82	pentachlorobenzene	ng	9,42
Be	µg	63,50	ethyne	µg	59,30	pentachlorophenol	ng	1,52
benzaldehyde	ng	45,50	Fe	mg	40,50	pentane	mg	139,00
benzene	mg	27,50	fluoranthene	µg	63,70	phenanthrene	µg	127,00
benzo(a)pyrene	µg	5,22	formaldehyde	mg	22,50	phenol	mg	1,09
benzo(k)fluoranthrene	µg	21,20	H2	µg	568,00	Phosphorus	µg	24,60
Br	mg	3,32	H2S	mg	47,80	propane	mg	233,00
butane	mg	132,00	H2SO4	g	16,90	propene	mg	4,70
butane (unspec.)	mg	4,19	HALON-1301	µg	524,00	propionaldehyde	ng	18,70
butene	mg	2,73	HCFC-21	µg	171,00	propionic acid	µg	365,00

Table G.2 (Cont'd): Life cycle inventory results – airborne emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Ca	mg	67,00	HCFC-22	µg	4,29	Pt	ng	190,00
Cd	mg	1,78	HCl	g	191,00	pyrene	µg	42,40
CF4	ng	615,00	HCN	ng	88,70	Sb	µg	263,00
CFC-11	µg	18,00	He	mg	81,10	Sc	µg	6,71
CFC-114	µg	475,00	heat losses	kJ	152,00	Se	mg	249,00
CFC-116	µg	19,90	heptane	mg	21,20	Si	mg	2,47
CFC-12	µg	3,87	hexachlorobenzene	ng	62,80	silicates	mg	156,00
CFC-13	µg	2,43	hexane	mg	44,50	Sn	µg	14,90
CFC-14	µg	178,00	HF	g	11,20	SO2	kg	3,21
CFC-21	µg	7,13	HFC-134a	pg	0,00	soot	µg	2,02
CFC (hard)	ng	2,70	Hg	mg	12,80	SOx	kg	2,24
Cl2	mg	4,20	hydrazine	mg	2,77	SOx (as SO2)	g	179,00
CN (complex)	ng	253,00	I	mg	1,50	Sr	µg	680,00
CO	kg	2,13	K	mg	11,70	sulphur	mg	975,00
CO2	kg	864,00	kerosene	mg	2,44	Te	kg	0,00
CO2 (fossil)	kg	216,00	La	µg	20,00	tetrachloroethene	µg	95,60
CO2 (non-fossil)	kg	11,60	MBTE	ng	138,00	tetrachloromethane	µg	297,00
cobalt	mg	12,20	metals	mg	26,10	Th	µg	12,90
Cr	mg	1,64	methane	kg	4,66	Ti	mg	1,92
Cr (VI)	mg	22,30	methanol	mg	14,90	Tl	µg	4,85
Cu	mg	54,10	Mg	mg	15,50	toluene	mg	19,30
CxHy	g	2,46	Mn	mg	27,50	trichloroethene	µg	92,50
CxHy (alkanes)	µg	104,00	Mo	µg	613,00	trichloromethane	µg	3,07
CxHy (alkenes)	µg	21,90	MTBE	µg	3,19	U	µg	14,30
CxHy (non methane)	mg	319,00	n-nitrodimethylamine	µg	20,80	V	mg	127,00
CxHy (sulph)	ng	1,62	N2	mg	737,00	vinyl chloride	µg	22,80
CxHy aromatic	mg	32,40	N2O	g	24,10	VOC	g	128,00

WATERBORNE EMISSIONS

Table G.3: Life cycle inventory results – waterborne emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
1,1-dichloroethene	ng	69,70	di(2-ethylhexyl)phthalate	ng	5,60	OCl-	mg	9,18
1,1,1-trichloroethane	ng	41,80	dibutyl p-phthalate	ng	102,00	oil	g	60,20
acenafthylene	µg	41,90	dibutylphthalate	ng	4,24	oil (animal/vegetable)	pg	4,27
acenaphthylene	mg	1,00	dichloroethane	µg	63,20	olefines	µg	21,60
Acid as H+	mg	8,94	dichloromethane	µg	865,00	ortho-xylene	µg	183,00
acid organic (as C)	mg	9,04	dimethyl p-phthalate	ng	640,00	other organics	g	9,65
acids (unspecified)	g	109,00	dimethylphtalate	ng	26,70	P-compounds	µg	52,30
Ag	µg	38,00	dioxins (TEQ)	ng	111,00	PAH's	µg	996,00
Al	g	2,55	dissolved organics	mg	1,83	Pb	mg	15,60
alkanes	mg	7,89	dissolved solids	kg	3,56	phenol	mg	2,78
alkenes	µg	730,00	dissolved substances	g	12,90	phenols	mg	10,60
anorg. Dissolved subst.	g	1,76	DOC	mg	55,20	phosphate	g	70,00
AOCl	µg	70,00	ethyl benzene	mg	1,42	Phosphorus	mg	3,88
AOX	µg	284,00	fats/oils	g	1,57	Polychlorinated furans (PCDF)	ng	96,40
arsenic	mg	1,08	fatty acids as C	mg	299,00	Ru	µg	590,00
As	mg	5,11	Fe	g	3,57	S	µg	4,75
asbestos	ng	1,04	fluoride ions	mg	29,20	salt	mg	17,80
B	mg	342,00	formaldehyde	ng	251,00	salts	g	2,94
Ba	mg	393,00	glutaraldehyde	µg	239,00	Sb	µg	19,30
baryte	g	1,93	H2	mg	4,48	Se	mg	5,70
Be	µg	1,98	H2S	µg	75,60	Si	mg	1,29
benzene	mg	8,20	H2SO4	mg	84,40	Sn	µg	11,00
BOD	g	384,00	heat losses	kJ	9,81	SO3	mg	1,20
Ca	mg	84,00	hexachloroethane	ng	1,33	Sr	mg	371,00
calcium compounds	mg	4,17	Hg	µg	29,50	sulphate	kg	2,56

Table G.3 (Cont'd): Life cycle inventory results – waterborne emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
calcium ions	g	3,55	HOCL	mg	9,29	sulphide	mg	2,50
Cd	mg	171,00	hydrazine	mg	16,50	suspended solids	kg	2,01
Ce	µg	1,76	hydroxy (ions)	pg	541,00	suspended substances	g	7,46
Chemical oxigen demand (COD)	g	3,98	I	mg	5,90	tetrachloroethene	ng	157,00
chlorinated solvents (unspec.)	µg	3,80	K	mg	631,00	tetrachloromethane	ng	241,00
chlorobenzene	pg	6,71	Kjeldahl-N	g	144,0	Ti	mg	65,90
chlorobenzenes	pg	188,00	MBTE	ng	11,40	titanium(IV)oxide	pg	14,50
chloroform	mg	11,80	metallic ions	mg	798,00	TOC	g	2,63
chromate	µg	534,00	methanol	g	2,27	toluene	mg	9,86
Cl-	g	319,00	Mg	g	1,02	tributyltin	µg	79,90
Co	mg	3,89	Mn	g	11,60	tributyltinoxide	µg	5,49
COD	g	27,80	Mo	mg	4,09	trichloroethene	µg	10,60
Cr	mg	179,00	MTBE	ng	264,00	trichloromethane	µg	36,60
Cr (III)	µg	22,60	N-tot	mg	366,00	triethylene glycol	mg	41,60
Cr (VI)	mg	10,60	N organically bound	mg	8,48	triethyleneglycol	mg	1,28
Cs	µg	57,40	Na	g	38,70	undissolved substances	g	7,08
Cu	mg	423,00	NH3	mg	235,00	V	mg	8,10
CxHy	mg	7,63	NH3 (as N)	g	22,3	vinyl chloride	ng	44,80
CxHy aliphatic	µg	19,20	NH4+	mg	40,00	VOC as C	mg	20,00
CxHy aromatic	mg	55,10	Ni	mg	13,00	W	µg	50,00
CxHy chloro	µg	29,70	nitrate	g	12,4	xylene	mg	5,71
cyanide	µg	750,00	nitrite	g	4,54	Zn	g	13,80
detergent/oil	mg	3,21	nitrogen	mg	241,00			

SOLID EMISSIONS

Table G.4: Life cycle inventory results – solid emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Abfaelle-Inertst.dep	g	1,98	HgOH (tw)	pg	0,66	slag	mg	37,30
Abfaelle-Restst.dep	mg	44,10	high active nuclear waste	mm3	0,04	slags/ash	mg	27,50
asbestos (tw)	ng	95,90	industrial waste	mg	2,29	solid waste	kg	7,44
Bauspgut-Inertst.dep	mg	85,20	inorganic general	mg	32,90	solid waste (nw)	mg	84,80
Beton-Inertst.dep	mg	65,80	Kat-Sonderabfalldep	mg	2,05	Stahl-Inertst.dep	mg	22,50
Bohrabfall-Landf	mg	294,00	Klkstrst-Inertst.dep	µg	13,40	Steinkohle-Asche-Dep	mg	337,00
Bohrabfall-Rstst.dep	mg	492,00	Kupfer-Inertst.dep	µg	1,28	Steinkohleberge-Dep	g	13,00
bottom ash (mswi)	mg	10,80	L/Mrad. waste (rw)	mm3	2,67	tailings	g	2,24
chemical waste (inert)	µg	917,00	mineral waste	mg	188,00	tailings (nw)	µg	18,00
Deckfarbe-Inrtst.dep	ng	19,30	mineral waste (mining)	g	239,00	waste	mg	19,60
Depnrte-Flugasche	mg	122,00	Minwolle-Inertst.dep	µg	69,90	waste bioactive landfill	g	82,40
diesel oil sludge (tw)	ng	56,00	produc. waste (not inert)	mg	198,00	waste in incineration	g	1,30
Erdgasl-Inertst.dep	mg	13,80	Rafschlamm-Landf	mg	2,45	waste in inert landfill	kg	61,80
FGC residues (mswi)	mg	1,03	Rckst-Entkrb-Restst.dep	mg	83,30	waste limestone	g	25,00
final waste (inert)	g	23,70	Rckst-Kuehlturmtassen	mg	6,80	Zeolithe-Inertst.dep	mg	1,23
fly ash (mswi)	mg	1,07	Schweissstaub-Sabf	ng	15,40			

EMISSIONS TO SOIL

Table G.5: Life cycle inventory results – emissions to soil

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Al (ind.)	mg	121,00	Cr (VI) (ind.)	g	2,72	oil (ind.)	mg	49,60
arsenic (ind.)	mg	556,00	Cu (ind.)	g	2,27	oil biodegradable	µg	165,00
As (ind.)	µg	48,50	dibenzo(a,h)anthracene (ind.)	µg	63,70	oil biological	µg	3,00
benzo(a)anthracene (ind.)	µg	233,00	dibenzo(a,i)pyrene (ind.)	µg	21,20	P-tot	mg	6,15
benzo(a)pyrene (ind.)	µg	127,00	Dioxin (TEQ) (ind.)	ng	1,27	Pb (ind.)	mg	890,00
benzo(b)fluoranthene (ind.)	µg	191,00	Fe (ind.)	mg	242,00	perylene	µg	21,20
benzo(e)pyren (ind.)	µg	212,00	fluoranthene (ind.)	µg	170,00	phenanthrene (ind.)	mg	1,95
benzo[ghi]perylene (ind.)	µg	212,00	Hg (ind.)	mg	5,07	pyrene	µg	255,00
C (ind.)	mg	371,00	indeno[1,2,3-cd]pyrene (ind.)	µg	42,40	S (ind.)	mg	72,80
Ca (ind.)	mg	485,00	Mn (ind.)	g	3,63	selenium (ind.)	mg	171,00
Cd (ind.)	µg	1,21	N	µg	63,00	vanadium (ind.)	g	4,13
Co (ind.)	mg	810,00	Ni (ind.)	g	1,87	Zn (ind.)	g	1,91
Cr (ind.)	µg	607,00	oil	mg	1,53			

NON MATERIAL EMISSIONS

Table G.6: Life cycle inventory results – non material emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Ag110m to air	µBq	23,30	Pu238 to air	nBq	51,80	Rad.wat-I133	µBq	1,88
Ag110m to water	mBq	159,00	Pu241 beta	Bq	5,66	Rad.wat-K-40	mBq	20,10
agric, trad;5;6;15;12	cm2a	24,50	Pu241 Beta to air	mBq	37,90	Rad.wat-La140	nBq	85,00
alpha radiation (unspecified) to water	µBq	18,90	Ra224 to water	Bq	2,86	Rad.wat-Mn54	mBq	12,90
Am241 to air	µBq	435,00	Ra226 to air	mBq	493,00	Rad.wat-Mo99	nBq	28,60
Am241 to water	mBq	57,30	Ra226 to water	kBq	1,06	Rad.wat-Na24	µBq	12,60
Ar41 to air	Bq	50,70	Ra228 to air	mBq	32,00	Rad.wat-Nb95	nBq	234,00
Ba140 to air	µBq	91,20	Ra228 to water	Bq	5,71	Rad.wat-Np237	µBq	24,50
Ba140 to water	µBq	286,00	Rad.air-Ag110m	nBq	378,00	Rad.wat-Nuklidmix	nBq	762,00
beta radiation (unspecified) to air	µBq	2,93	Rad.air-Am241	µBq	2,91	Rad.wat-Pa234m	mBq	1,73
C14 to air	Bq	34,90	Rad.air-Andere-Beta	nBq	9,24	Rad.wat-Pb-210	mBq	16,00
C14 to water	Bq	2,90	Rad.air-Ar41	mBq	825,00	Rad.wat-Po-210	mBq	16,00
Cd109 to water	µBq	1,65	Rad.air-Ba140	nBq	626,00	Rad.wat-Pu-alpha	mBq	1,52
Ce141 to air	µBq	2,17	Rad.air-C14	mBq	223,00	Rad.wat-Pu241-beta	mBq	37,90
Ce141 to water	µBq	42,80	Rad.air-Ce141	nBq	11,30	Rad.wat-Ra-224	mBq	88,10
Ce144 to air	mBq	4,63	Rad.air-Ce144	µBq	31,00	Rad.wat-Ra-226	Bq	7,28
Ce144 to water	Bq	1,31	Rad.air-Cm-alpha	µBq	4,61	Rad.wat-Ra-228	mBq	176,00
Cm (alpha) to air	µBq	690,00	Rad.air-Cm242	nBq	0,02	Rad.wat-Ru103	nBq	138,00
Cm (alpha) to water	mBq	75,90	Rad.air-Cm244	nBq	0,16	Rad.wat-Ru106	mBq	92,50
Cm242 to air	nBq	2,30	Rad.air-Co57	nBq	0,66	Rad.wat-Sb122	nBq	411,00
Cm244 to air	nBq	20,80	Rad.air-Co58	µBq	3,48	Rad.wat-Sb124	µBq	57,30
Co57 to air	nBq	40,10	Rad.air-Co60	µBq	5,43	Rad.wat-Sb125	µBq	3,35
Co57 to water	µBq	293,00	Rad.air-Cr51	nBq	495,00	Rad.wat-Sp-u-Activ-pr	mBq	4,34

Table G.6 (Cont'd): Life cycle inventory results – non material emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
Co58 to air	µBq	664,00	Rad.air-Cs134	µBq	110,00	Rad.wat-Sr89	nBq	930,00
Co58 to water	mBq	248,00	Rad.air-Cs137	µBq	213,00	Rad.wat-Sr90	mBq	18,50
Co60 to air	µBq	987,00	Rad.air-Edelgase	mBq	4,36	Rad.wat-Tc99	mBq	9,71
Co60 to water	Bq	12,70	Rad.air-Fe59	nBq	8,19	Rad.wat-Tc99m	nBq	194,00
Conv. to industrial area	mm2	3,08	Rad.air-H3	Bq	2,26	Rad.wat-Te123m	nBq	17,40
Cr51 to air	µBq	82,00	Rad.air-I129	µBq	832,00	Rad.wat-Te132	nBq	7,12
Cr51 to water	mBq	6,29	Rad.air-I131	µBq	124,00	Rad.wat-Th-228	mBq	352,00
Cs134 to air	mBq	16,50	Rad.air-I133	µBq	40,00	Rad.wat-Th-232	mBq	3,74
Cs134 to water	Bq	2,93	Rad.air-I135	µBq	60,10	Rad.wat-Th230	mBq	270,00
Cs136 to water	µBq	1,53	Rad.air-K40	mBq	1,24	Rad.wat-Th234	mBq	1,74
Cs137 to air	mBq	31,90	Rad.air-Kr85	kBq	14,30	Rad.wat-U-238	mBq	13,10
Cs137 to water	Bq	26,90	Rad.air-Kr85m	mBq	19,20	Rad.wat-U-alpha	mBq	113,00
drill gas, land;0;0;15;12	cm2a	11,10	Rad.air-Kr87	mBq	13,10	Rad.wat-U234	mBq	2,30
drill gas,sea;15;12;15;12	m2a	0,00	Rad.air-Kr88	mBq	529,00	Rad.wat-U235	mBq	3,44
drill oil, land;0;0;15;6	mm2a	245,00	Rad.air-Kr89	mBq	9,37	Rad.wat-Y90	nBq	47,50
drill oil, sea;15;6;15;6	m2a	0,00	Rad.air-La140	nBq	312,00	Rad.wat-Zn65	µBq	26,70
dump hrw;0;0;15;12	m2s	21,60	Rad.air-LT-Rd-Rn222	kBq	20,80	Rad.wat-Zr95	µBq	786,00
dump lmrw;0;0;15;12	m2s	8,49	Rad.air-Mn54	nBq	130,00	radio active noble gases to air	Bq	3,03
dump rw;0;0;15;12	cm2a	11,40	Rad.air-Nb95	nBq	57,70	radioactive substance to air	kBq	5060,00
Fe59 to air	nBq	907,00	Rad.air-Np237	nBq	0,15	radioactive substance to water	kBq	44,80
Fe59 to water	µBq	5,06	Rad.air-Pa234m	µBq	93,40	radionuclides (mixed) to water	µBq	124,00
Fission and activation products (RA) to water	mBq	172,00	Rad.air-Pb210	mBq	5,34	Rn220 to air	Bq	3,03
H3 to air	Bq	361,00	Rad.air-Pm147	µBq	78,60	Rn222 (long term) to air	kBq	3070,00
H3 to water	kBq	85,90	Rad.air-Po-210	mBq	7,96	Rn222 to air	kBq	33,40

Table G.6 (Cont'd): Life cycle inventory results – non material emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
heat losses to air	MJ	1,97	Rad.air-Po210	mBq	1,03	Ru103 to air	nBq	237,00
heat losses to soil	J	319,00	Rad.air-Pu-alpha	µBq	9,25	Ru103 to water	µBq	95,90
heat losses to water	kJ	35,80	Rad.air-Pu238	nBq	0,45	Ru106 to air	mBq	138,00
hydro;0;0;10;7	mm2a	39,40	Rad.air-Pu241-Beta	µBq	255,00	Ru106 to water	Bq	13,80
I129 to air	mBq	124,00	Rad.air-Ra226	mBq	4,03	Sb122 to water	µBq	286,00
I129 to water	Bq	8,28	Rad.air-Ra228	µBq	614,00	Sb124 to air	µBq	6,41
I131 to air	mBq	13,80	Rad.air-Rn220	mBq	156,00	Sb124 to water	mBq	41,00
I131 to water	mBq	5,48	Rad.air-Rn222	Bq	226,00	Sb125 to air	nBq	815,00
I133 to air	mBq	7,72	Rad.air-Ru103	nBq	3,96	Sb125 to water	mBq	2,33
I133 to water	mBq	1,31	Rad.air-Ru106	µBq	925,00	Sr89 to air	µBq	41,50
I135 to air	mBq	11,60	Rad.air-Sb124	nBq	95,80	Sr89 to water	µBq	647,00
□ndus;5;1;15;12	mm2a	566,00	Rad.air-Sb125	nBq	13,70	Sr90 to air	mBq	22,80
K40 to air	mBq	65,30	Rad.air-Sr89	nBq	209,00	Sr90 to water	Bq	2,77
K40 to water	mBq	208,00	Rad.air-Sr90	µBq	152,00	Tc99 to air	nBq	966,00
Kr85 to air	kBq	2140,00	Rad.air-Tc99	nBq	6,47	Tc99 to water	Bq	1,45
Kr85m to air	Bq	2,52	Rad.air-Te123m	µBq	1,70	Tc99m to water	µBq	135,00
Kr87 to air	Bq	1,13	Rad.air-Th228	µBq	524,00	Te123m to air	µBq	104,00
Kr88 to air	Bq	101,00	Rad.air-Th230	mBq	1,03	Te123m to water	µBq	12,10
Kr89 to air	mBq	792,00	Rad.air-Th232	µBq	331,00	Te132 to water	µBq	4,94
La140 to air	µBq	57,70	Rad.air-Th234	µBq	93,40	Th228 to air	mBq	27,10
La140 to water	µBq	59,30	Rad.air-U-alpha	mBq	3,34	Th228 to water	Bq	11,40
land use (sea floor) II-III	m2a	0,15	Rad.air-U234	mBq	1,12	Th230 to air	mBq	154,00
land use (sea floor) II-IV	cm2a	156,00	Rad.air-U235	µBq	54,10	Th230 to water	Bq	40,00
land use II-III	m2a	0,22	Rad.air-U238	mBq	2,04	Th232 to air	mBq	17,20
land use II-III bento	cm2a	34,80	Rad.air-Xe131m	mBq	86,80	Th232 to water	mBq	38,70
land use II-IV	cm2a	92,00	Rad.air-Xe133	Bq	8,53	Th234 to air	mBq	13,80
land use II-IV bento	mm2a	360,00	Rad.air-Xe133m	mBq	11,20	Th234 to water	mBq	258,00

Table G.6 (Cont'd): Life cycle inventory results – non material emissions

Substance	Unit	Total	Substance	Unit	Total	Substance	Unit	Total
land use III-IV	cm2a	166,00	Rad.air-Xe135	Bq	1,55	trans, canal;5;5;15;12	m2s	35,40
land use IV-IV	cm2a	17,20	Rad.air-Xe135m	mBq	291,00	trans, roadNL;5;2;15;12	mm2a	35,00
minin Ni; 0;0;10;8	mm2a	117,00	Rad.air-Xe137	mBq	10,80	trans,rail NL;5;2;15;12	mm2a	297,00
minin rocks.;0;0;15;12	m2s	0,03	Rad.air-Xe138	mBq	79,20	U alpha to air	mBq	495,00
minin U;0;0;17;8	m2s	164,00	Rad.air-Zn65	nBq	583,00	U alpha to water	Bq	16,70
mining coal;0;0;25;9	mm2a	489,00	Rad.air-Zr95	nBq	22,10	U234 to air	mBq	166,00
Mn54 to air	µBq	23,70	Rad.wat-Ag110m	µBq	222,00	U234 to water	mBq	342,00
Mn54 to water	Bq	1,94	Rad.wat-Alpha-Strahler	nBq	109,00	U235 to air	mBq	8,02
Mo99 to water	µBq	20,00	Rad.wat-Am241	µBq	384,00	U235 to water	mBq	510,00
Na24 to water	mBq	8,82	Rad.wat-Ba140	nBq	411,00	U238 to air	mBq	212,00
Nb95 to air	µBq	4,19	Rad.wat-C14	mBq	19,40	U238 to water	mBq	865,00
Nb95 to water	µBq	162,00	Rad.wat-Cd109	nBq	2,38	waste heat to air	MJ	123,00
Np237 to air	nBq	22,80	Rad.wat-Ce141	nBq	61,30	waste heat to soil	kJ	212,00
Np237 to water	mBq	3,66	Rad.wat-Ce144	mBq	8,77	waste heat to water	MJ	4,16
Occup. as forest land	m2y	32900,00	Rad.wat-Cm-alpha	µBq	508,00	Xe131m to air	Bq	5,22
Occup. as industrial area	mm2a	832,00	Rad.wat-Co57	nBq	419,00	Xe133 to air	kBq	1,54
Pa234m to air	mBq	13,80	Rad.wat-Co58	µBq	351,00	Xe133m to air	mBq	774,00
Pa234m to water	mBq	256,00	Rad.wat-Co60	mBq	83,60	Xe135 to air	Bq	262,00
Pb210 to air	mBq	383,00	Rad.wat-Cr51	µBq	9,04	Xe135m to air	Bq	25,80
Pb210 to water	mBq	166,00	Rad.wat-Cs134	mBq	19,50	Xe137 to air	mBq	641,00
pipel;5;0;15;12	cm2a	95,50	Rad.wat-Cs136	nBq	2,21	Xe138 to air	Bq	7,01
Pm147 to air	mBq	11,70	Rad.wat-Cs137	mBq	180,00	Y90 to water	µBq	33,10
Po210 to air	mBq	573,00	Rad.wat-Fe59	nBq	7,28	Zn65 to air	µBq	102,00
Po210 to water	mBq	166,00	Rad.wat-H3	Bq	574,00	Zn65 to water	mBq	18,60
Pu alpha to air	mBq	1,38	Rad.wat-I129	mBq	55,40	Zr95 to air	µBq	1,52
Pu alpha to water	mBq	228,00	Rad.wat-I131	µBq	7,71	Zr95 to water	mBq	117,00

APPENDIX H: CONTRIBUTION ANALYSIS RESULTS

Table H.1: Process contribution (%) to category indicator results

Unit process	Global warming	Ozone depletion	Eutrophication	Acidification	Smog formation	Eco-toxicity	Human health cancer	Human health non cancer	Human health criteria pollutants
FOREGROUND SYSTEM	**24,07**	**0,00**	**86,16**	**10,40**	**40,47**	**0,60**	**0,17**	**3,34**	**23,75**
Termomechanical pulping	0,02	0,00	0,00	0,00	2,09	0,00	0,00	0,00	0,00
Natural gas combustion (*Heat from natural gas*)	10,50	0,00	1,75	2,00	6,92	0,00	0,00	0,00	1,40
Biomass combustion	0,41	0,00	4,49	5,46	18,34	0,00	0,00	0,00	6,92
Heat from hogfuel	*0,32*	*0,00*	*3,46*	*4,21*	*14,20*	*0,00*	*0,00*	*0,00*	*5,33*
Heat from sludge	*0,09*	*0,00*	*1,03*	*1,25*	*4,14*	*0,00*	*0,00*	*0,00*	*1,59*
Newsprint mill effluent (*Effluent treatment*)	0,00	0,00	77,52	0,02	0,00	0,60	0,06	2,43	0,00
Landfill industrial	7,87	0,00	0,02	0,00	0,40	0,00	0,00	0,00	0,00
Transportation	5,27	0,00	2,37	2,92	12,72	0,00	0,11	0,91	15,43
Supply transportation by truck *(Trailer diesel per gal)*	*2,14*	*0,00*	*1,03*	*1,27*	*5,12*	*0,00*	*0,00*	*0,00*	*4,76*
Distribution transportation by truck *(Trailer diesel per tkm)*	*1,48*	*0,00*	*0,71*	*0,88*	*3,53*	*0,00*	*0,00*	*0,00*	*3,28*
Supply transportation by rail *(Locomotive Diesel per gal)*	*0,31*	*0,00*	*0,13*	*0,17*	*0,87*	*0,00*	*0,00*	*0,00*	*1,52*
Distribution transportation by rail *(Locomotive Diesel per tkm)*	*1,08*	*0,00*	*0,46*	*0,57*	*3,01*	*0,00*	*0,00*	*0,00*	*5,24*
Propane vehicles	*0,08*	*0,00*	*0,01*	*0,01*	*0,04*	*0,00*	*0,00*	*0,00*	*0,00*
Truck (single) gasoline	*0,14*	*0,00*	*0,02*	*0,03*	*0,15*	*0,00*	*0,11*	*0,91*	*0,63*
Aviation turbo	*0,04*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*

Table H.1 (Cont'd): Process contribution (%) to category indicator results

Unit process	Global warming	Ozone depletion	Eutrophication	Acidification	Smog formation	Eco-toxicity	Human health cancer	Human health non cancer	Human health criteria pollutants
BACKGROUND SYSTEM	**75,92**	**99,96**	**13,84**	**89,59**	**59,60**	**99,44**	**99,87**	**96,66**	**76,25**
Electricity production *(Electricity Ontario)*	70,90	0,00	11,06	55,00	32,40	94,70	87,70	74,00	52,70
Fuel production	2,94	3,03	1,58	30,64	23,06	1,39	2,21	16,46	20,93
Natural gas	*2,31*	*2,12*	*1,35*	*29,50*	*18,90*	*0,84*	*1,12*	*15,20*	*19,80*
Destillate Fuel Oil (DFO)	*0,60*	*0,87*	*0,22*	*1,08*	*3,97*	*0,53*	*1,04*	*1,21*	*1,08*
LPG FAL	*0,01*	*0,02*	*0,00*	*0,02*	*0,07*	*0,01*	*0,02*	*0,02*	*0,02*
Gasoline FAL-c	*0,02*	*0,02*	*0,01*	*0,03*	*0,10*	*0,01*	*0,03*	*0,03*	*0,03*
Kerosene I	*0,00*	*0,00*	*0,00*	*0,01*	*0,01*	*0,00*	*0,00*	*0,00*	*0,01*
Chemical production	2,07	96,94	1,20	3,95	4,14	3,35	9,96	6,20	2,62
Ammonia ETH T	0,20	3,77	0,15	0,23	0,48	0,17	0,28	0,27	0,06
Borol	0,37	20,87	0,20	0,56	0,60	0,89	1,64	1,45	0,51
Borol	*0,00*	*0,00*	*0,07*	*0,00*	*0,06*	*0,00*	*0,00*	*0,00*	*0,00*
Coal FAL	*0,01*	*0,04*	*0,00*	*0,00*	*0,01*	*0,01*	*0,01*	*0,01*	*0,11*
Coal into electricity boilers-c	*0,15*	*0,55*	*0,06*	*0,22*	*0,22*	*0,42*	*0,31*	*0,32*	*0,13*
Coal into industrial boilers	*0,01*	*0,00*	*0,00*	*0,01*	*0,01*	*0,01*	*0,20*	*0,03*	*0,01*
DFO into electricity boilers	*0,00*	*0,02*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*
Natural gas FAL	*0,01*	*0,01*	*0,00*	*0,07*	*0,05*	*0,00*	*0,00*	*0,04*	*0,05*
Nat. gas into electr. boilers	*0,01*	*0,00*	*0,00*	*0,01*	*0,02*	*0,00*	*0,00*	*0,00*	*0,00*
Nat. gas into industr. boilers	*0,01*	*0,00*	*0,00*	*0,01*	*0,01*	*0,00*	*0,00*	*0,00*	*0,00*
RFO into electricity boilers	*0,00*	*0,25*	*0,00*	*0,01*	*0,00*	*0,00*	*0,03*	*0,01*	*0,00*
Uranium in electricity boilers	*0,00*	*0,01*	*0,00*	*0,01*	*0,01*	*0,00*	*0,00*	*0,00*	*0,02*
H2 ETH T	*0,16*	*20,00*	*0,05*	*0,23*	*0,21*	*0,44*	*1,07*	*1,04*	*0,18*
Chemicals inorganic ETH T-c	0,07	14,80	0,03	0,16	0,11	0,26	0,79	0,72	0,14
Chemicals organic ETH T-c	0,21	27,30	0,08	0,25	0,22	0,25	2,39	1,15	0,20
H2O2	0,31	0,98	0,24	0,56	0,99	0,50	0,64	0,47	0,40
H2O2, manufacturing (IIASA)	*0,07*	*0,00*	*0,15*	*0,18*	*0,61*	*0,00*	*0,00*	*0,00*	*0,03*

Table H.1 (Cont'd): Process contribution (%) to category indicator results

Unit process	Global warming	Ozone depletion	Eutrophication	Acidification	Smog formation	Eco-toxicity	Human health cancer	Human health non cancer	Human health criteria pollutants
Coal FAL	*0,01*	*0,04*	*0,00*	*0,01*	*0,01*	*0,01*	*0,02*	*0,01*	*0,12*
Coal into electricity boilers-c	*0,17*	*0,61*	*0,07*	*0,25*	*0,25*	*0,47*	*0,35*	*0,36*	*0,15*
Coal into industrial boilers	*0,01*	*0,00*	*0,00*	*0,01*	*0,01*	*0,01*	*0,22*	*0,03*	*0,01*
DFO into electricity boilers	*0,00*	*0,02*	*0,00*	*0,00*	*0,00*	*0,00*	*0,01*	*0,00*	*0,00*
Natural gas FAL	*0,01*	*0,01*	*0,00*	*0,08*	*0,05*	*0,00*	*0,00*	*0,04*	*0,05*
Nat. gas into electr. boilers	*0,01*	*0,00*	*0,01*	*0,01*	*0,02*	*0,00*	*0,00*	*0,00*	*0,00*
Nat. gas into industr. boilers	*0,01*	*0,00*	*0,00*	*0,01*	*0,02*	*0,00*	*0,00*	*0,00*	*0,00*
RFO into electricity boilers	*0,01*	*0,28*	*0,00*	*0,01*	*0,00*	*0,00*	*0,03*	*0,01*	*0,00*
Uranium in electricity boilers	*0,00*	*0,01*	*0,00*	*0,01*	*0,01*	*0,01*	*0,00*	*0,00*	*0,02*
H2SO4 ETH T	0,01	0,53	0,00	0,04	0,01	0,03	0,08	0,05	0,03
Lime B250	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
NaOH	0,43	12,90	0,34	0,90	1,50	0,68	3,05	1,05	0,43
NaSiO3	0,06	0,23	0,01	0,02	0,03	0,16	0,06	0,12	0,01
Electricity from coal B250	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,03*	*0,01*	*0,00*
Electricity from oil B250	*0,00*	*0,09*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*
Heat diesel B250	*0,00*	*0,06*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*	*0,00*
Heat gas B250	*0,06*	*0,08*	*0,01*	*0,01*	*0,03*	*0,15*	*0,03*	*0,11*	*0,00*
Phosphoric acid ETH T	0,11	15,10	0,04	0,32	0,13	0,36	1,00	0,83	0,24
Soap	0,29	0,45	0,12	0,08	0,07	0,04	0,05	0,08	0,04
Coal NL (ETH)	*0,00*	*0,15*	*0,00*	*0,00*	*0,00*	*0,00*	*0,01*	*0,03*	*0,00*
Crude palm oil-c	*0,24*	*0,00*	*0,11*	*0,04*	*0,03*	*0,00*	*0,00*	*0,00*	*0,02*
Diesel precomb # ETH3	*0,00*	*0,20*	*0,00*	*0,00*	*0,00*	*0,00*	*0,01*	*0,01*	*0,00*
Electr. Low V. UCPTE	*0,00*	*0,03*	*0,00*	*0,00*	*0,00*	*0,00*	*0,01*	*0,01*	*0,00*
MJel NL # (ETH3)	*0,01*	*0,08*	*0,00*	*0,01*	*0,01*	*0,02*	*0,01*	*0,03*	*0,00*
Steam (kg)	*0,03*	*0,00*	*0,01*	*0,02*	*0,02*	*0,00*	*0,00*	*0,00*	*0,01*
Sulphur dioxide B250	0,00	0,00	0,00	0,84	0,00	0,00	0,00	0,00	0,57